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(71) Applicant *(for all designated States except US)*: **TEST-SHIP AUTOMATIC TEST SOLUTIONS LTD.** [IL/IL]; P.O. Box 9, 24959 Tefen (IL).

(72) Inventors; and

(75) Inventors/Applicants *(for US only)*: **MAKMEL, Ilan** [IL/IL]; 7 Alon St., 25147 Kfar Vradim (IL). **DROR, Meir** [IL/IL]; 1 Hahavazelet St., 27100 Kiryat Bialik (IL).

(74) Agent: **FRIEDMAN, Mark, M.**; 7 Haomanim St., 67897 Tel Aviv (IL).

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(54) Title: PROBE, SYSTEMS AND METHODS FOR INTEGRATED CIRCUIT BOARD TESTING

(57) Abstract: A probe with a plurality of probe tips, useful for the electronic testing of electronic assemblies is disclosed. Further, a system for testing electronic assemblies as well as methods for testing electronic assemblies are disclosed, based on the use of a plurality of independently manoeuvrable probes each having a plurality of probe tips.

PROBE, SYSTEMS AND METHODS FOR INTEGRATED CIRCUIT BOARD TESTING

FIELD AND BACKGROUND OF THE INVENTION

The present invention relates to the inspection of electronic assemblies and, more specifically, to an innovative probe, a testing system and methods for testing integrated circuit boards.

Modern electronic devices are most often constructed by installing electronic components onto a printed circuit board (PCB). The first step in the production of such an electronic device is the manufacture of a PCB. Conductive channels or wires are printed onto a non-conductive substrate. The conductive channels make up the PCB circuitry by connecting points on the PCB to the PCB edge connector or by connecting between points on the PCB.

After the circuitry is printed, the PCB is populated to give an ICB (Integrated Circuit Board). Passive components, such as resistors and capacitors, and active components, such as integrated circuits, are attached to the PCB so that the leads of the components make electrical contact with the proper points of the circuitry. Once all the components have been installed in the proper place, the printed circuitry interconnects the components to form the ICB that is the required electronic device.

As in any complex manufacturing process various faults occur. After assembly, an ICB must be tested, and while being tested is referred to as a UUT (Unit Under Test).

One method to test the UUT is through physical contact to "nodes": components, component-leads or specific points on the printed circuitry. The contact is made by probe-tips that are electrically connected to electronic diagnostic equipment. Once contact has been made two types of tests can be performed: 1) RLC (resistance, inductance and capacitance) parameters are measured to test component and circuit integrity and 2) a signal can be applied through one or more nodes and a corresponding response measured to determine component and circuit functionality and integrity.

One significant difficulty encountered by physical contact testing systems is in locating the nodes of the UUT.

Ideally, contact is made directly to the leads of a component to be tested. A testing system, knowing the topology of a UUT, should be able to deploy probe-tips to make contact with component-leads according to their designed coordinates. However, as in any manufacturing process, components are mounted on PCBs within a certain tolerance, making

the location of the leads uncertain. It may occur that due to tight-spacing or relatively small size of components, the leads themselves are accessible only with difficulty.

In order to make nodes accessible and to compensate for deviations in component placement, dedicated "test pads" are often printed in electrical contact with the points whereto component-leads connect once the components are installed. A test pad is a conductive cul-de-sac that serves no purpose other than being a physically accessible and locatable point through which electrical contact can be conveniently made to an installed component.

However, the deviation of the location of the printed circuitry on a PCB relative to the substrate is relatively large. Thus, *a priori*, the actual physical location of any node is uncertain. A solution to make nodes, such as test pads, locatable, is the use of one or more distinctive and identifiable fiducial points printed onto a PCB using the same template as used to print the circuitry itself. As a first step of testing, the fiducial points are located, for instance by optical observation. Thereafter, the location of the printed elements of the UUT such as circuitry and test pads can be found with reference to the fiducial points.

An important factor that must be considered when designing physical contact testing systems is the number of nodes that can be simultaneously contacted. The first reason is speed of testing. Whereas individual electronic tests are very quick, in the order of milliseconds, the physical maneuvering necessary to bring probe-tips in contact with UUT nodes is time consuming, taking in the order of seconds. Thus the more nodes a testing system is able to contact simultaneously, the more tests can be performed in a given period of time and the more rigorously a UUT can be tested within a reasonable period of time. Furthermore, the greater the number of nodes that can be simultaneously contacted the greater the complexity and thus the greater the variety of the tests that can be potentially performed. In some cases, a large number of nodes must be contacted to perform a test, for instance, to rigorously test a multi-lead active component or when a functionality test is performed.

In the art, there are two primary types of physical contact test systems for the testing of ICBs: flying probe systems and ICT (in circuit testing) systems.

Flying probes systems are typically equipped with one or more independently maneuverable robotic arms tipped with an electronic probe. The probe usually is equipped with one probe-tip, although configurations with multiple-tipped probes have been described. For a given UUT, a test protocol is formulated, comprising a series of individual electronic tests. Each step in the series includes bringing the probe-tips in contact with nodes followed by performing the desired electronic tests. Most often the probes are directed to test pads

whose location is determined relative to fiducial points as described above. Once contact has been made, RLC parameters of components are tested. Defects such as short circuits or components that are damaged, improperly installed, or missing are detected in this way.

The greatest advantage of the flying probe systems is that they are fixtureless: individual probes can be brought in contact with any node. Thus, flying probe systems can be programmed to test different UUTs.

Another advantage of the flying probe systems is that the maneuverability of the individual probes allows contact to be made directly with soldering pads whereto component-leads are connected instead of with test pads with reference to the fiducial point.

Two factors that severely limit the utility of flying probes systems result from the relatively limited number of probe-tips that can simultaneously make contact with UUT nodes.

The first factor is that even when using fiducial point guidance, this method is inherently slow. Rigorous testing of a UUT requires that many hundreds of individual electronic tests be performed. For a rigorous test to be performed frequent, time-consuming probe maneuvering is needed.

Another limitation resulting from the small number of probes is the limitation imposed on the nature and complexity of tests that can be performed.

Some specific tests require contact with many nodes. Although multi-probe systems deploying, for instance, twelve independently maneuverable probes on either side (top and bottom) of a UUT have been developed, the number of probe-tips simultaneously contacting UUT nodes to perform a single test is limited. Due to spatial limitations over the surface of the UUT and the dimensions of the robotic arms of testing systems, the maximal number of probes that can be in one flying probe system is limited, severely limiting the ability to perform more complex tests, especially around any one single component. For example, no currently available flying probe system is able to perform a test on a single component having more than four leads.

The second type of physical contact testing of ICBs is done using ICT. In ICT systems, a fixture (TUA, Test Unit Adapter) dedicated to the testing of one type of UUT is made. The TUA resembles a bed of nails, hence the popular name of ICT systems. The fixture is configured to be a supporting frame for the UUT with a bottom surface from which a plurality of probe-tips emerge. The frame holds the UUT in place while the probe-tips make contact with test pads, or in the case of through-board attachment of components, with the

component-leads extending through UUT substrate. Once a UUT is properly placed within the fixture, specific electronic tests are done simultaneously or in quick succession. Complete testing of a UUT using an ICT system is significantly faster than when using a flying probe system as no probe-tip maneuvering is needed.

A disadvantage of ICT systems is the high price of the TUA that must be custom made for each type of UUT. Further the TUA probe tips are typically fine and mechanically weak leading to a high maintenance overhead, and the contact pressure is not accurately controllable.

A further disadvantage of ICT systems is that the individual probe-tips are not maneuverable. As a result, the test-pads necessary for ICT systems are generally larger than those designed for use with flying probe systems.

It is possible to combine an ICT system with a flying probe system for increasing testing flexibility, as disclosed in US Patent 5,469,064. Although very useful, it is clear to one skilled in the art that such a combined system retains many of the disadvantages of both systems.

A testing method that can be used to increase the utility of contact testing systems is commonly known as a cluster test. A selected group of components (a cluster) of components is tested as a group, the group being electronically delineated by a plurality of nodes. The cluster testing method is useful when it is necessary to see that a specific cluster functions properly as a cluster, or when specific components in the cluster are inaccessible for whatever reason, such as the lack of test pads or other considerations. RLC characteristics as well as cluster functionality are tested. Descriptions of aspects of cluster testing can be found, for example in US 4,194,113, US 5,127,009 and the references therein, which are all incorporated by reference for all purposes as if fully set forth herein.

Cluster tests are exceptionally useful when applied using ICT systems as the large numbers of nodes contacted allows many different cluster tests to be performed. Cluster tests allow ICT systems to test components which are otherwise inaccessible due to the lack of test pads, albeit within the framework of a cluster.

Cluster tests are also exceptionally useful when applied using flying probe systems. Clusters are delineated by a number of nodes up to the number of probe-tips available to the system. Cluster tests allow faster and more complex tests to be performed than usual for a flying probe system.

It is important to note, however, that although very important, cluster testing cannot be considered a rigorous method for testing a UUT: often the electronic characteristics of a cluster are sufficient to pass a test but those of one or more components making up the cluster are not.

Newer generations of ICB manufacture technologies have introduced new challenges to testing for which the above-described testing systems are not sufficient. The increasing requirement for electronic devices with increasingly higher performance means that ICBs become compact and more densely populated while components become smaller and more complex. New technologies allow the production of densely populated ICBs with more closely spaced components. This often forces designers to leave out test pads necessary for contact testing systems. In the first place, it is preferable to use the space formerly reserved for test pads to add components. Second, designing an ICB with test pads is an effort that makes ICB design more expensive than otherwise. Lastly, as the distance between components gets smaller and operating frequencies get higher, test pads make RLC parameters increasingly complex due to impedance considerations and can even act as antennas. Thus the integration of test pads on densely populated ICBs can compromise function.

Non-contact testing methods have been developed to partially compensate for the difficulties in implementing effective physical contact testing for newer generations of ICBs.

One non-contact testing method is AOI (Automatic Optical Inspection). In AOI an optical imaging system is used to visually scan the UUT and, using image-processing techniques, the images found are compared to the expected UUT topology, for example as described by computer-aided design (CAD) data.

Another non-contact testing methods known in the art is known as a boundary scan, such as JTAG testing described by IEEE Standard 1149.1 (see, e.g., Maunder et al., entitled "The Test Access Port and Boundary-Scan Architecture," IEEE Computer Society of Press Tutorial, chapter 4, pp. 33-49 (1990)). By running signals through a D_{in} / D_{out} planned into the UUT, a boundary scan is performed to identify short circuits and damaged components. This test is most often performed through the UUT edge connector.

Another non-contacting testing method is functionality testing where the UUT is connected to a testing device through the UUT edge connector. Functionality testing checks selected UUT functions rather than board structure. This test is limited to primary input / output.

Flying probe testing system configured to allow performance of functionality test or boundary scan test while making physical contact at selected nodes on the UUT have been developed.

A drawback of both functionality test and boundary scan tests is that they must be performed "power-on". If power is applied to a UUT with short circuits or missing or damaged components, serious damage, some undetectable, may be caused to the UUT. It is thus preferable to precede power-on tests with physical contact tests.

ICBs made using multilayer PCBs where the conductive channels are buried inside the substrate or connections to components attached to the ICB through the use of ball-grid array (BGA) technology cannot be tested by contact or optical observation systems. X-ray imaging devices coupled with pattern recognition algorithms are used to test such ICBs. Although it would be advantageous to integrate an X-ray imaging system with contact testing systems, combined systems are not available. One reason is that X-ray imaging systems need to project X-rays through a UUT. Thus a UUT in an X-ray imaging system must be held in position around its periphery. When tested in contact testing systems, in particular ICT systems, UUTs are held within fixtures that preclude projection of X-rays through a UUT without parts of the fixture obstructing the path of the X-rays.

There is a need for a contact testing system for the inspection of compact and densely populated PCBs. Since there is a great variation in UUT architecture, the system must be adaptable in order to be able to efficiently and quickly test many variations of UUT. The system must be robust and able to make repeated, high-throughput contact with a UUT. Problems with the contact elements (probe-tips) of the system must be easily diagnosable and repairable with little down-time. The system must have small and highly maneuverable contact elements that can make simultaneous multiple contacts with high-pitch leads of closely spaced components. The system must be able to compensate for printing and component attachment errors. The system must be able to make contact with component-leads to eliminate the need for test pads. The systems must be able to make simultaneous contact to a multiplicity of nodes to reduce the number of physical maneuvers necessary to rigorously test a single UUT and to allow performance of tests that require contact with multiple nodes.

SUMMARY OF THE INVENTION

The probe, the diagnostic system and the testing methods provided by the present invention achieve the above and other objectives. The central element of the present invention

is a probe with a heretofore-unknown large number of probe-tips able to make physical contact with UUT nodes in order to test the UUT. Within the framework of a testing system of the present invention, a plurality of these probes are deployed by flying-probe type arms allowing exceptionally efficient and thorough testing of a UUT. Further, these probes are configured to be exchangeable so that each robotic arm can deploy a variety of probes, each with a different probe tip arrangement. In such a way, the system as a whole is made adaptable to test a large variety of component package geometry and differing UUT configurations. Further, if a probe is damaged, the probe is quickly and easily replaced "on-the-fly". The exceptional compact and lightweight yet rigid construction of the probe and robotic arms allows the system to deploy the arms at high accelerations, even up to 0.2 G without damaging the probes or other system components.

According to the teachings of the present invention there is provided a probe for the testing of electronic assemblies made up of a) a non-conductive probe body; b) at least two conductive probe tips rigidly attached to the probe body; and c) conductive channels such as wire, connected to each one of the probe tips. The probe body is preferably laminated and substantially planar. The conductive channels allow each one of the probe tips to be independently registerable by electronic measuring instrumentation. According to a feature of the present invention, the conductive channels are printed onto the probe body using printed circuit technology, and are preferable printed to be electrically shielded.

According to a further feature of the present invention, the probe tips are spring loaded in order to compensate for different heights when contact with the UUT is made or to accommodate tolerances and vibrations.

According to a feature of the present invention, the probe body is thin, as little as 5.0 mm thick, preferably less than 3.0 mm thick, and even more preferably less than 1.5 mm thick, and most preferably less than 1.3 mm thick.

In order to properly test a variety of component packages, it is clear that individual probes of the present invention must have various numbers of probe tips. Although two is the minimal number of probe tips of a probe of the present invention, a probe of the present invention can be configured to have at least five, preferably ten, more preferably twenty, even more preferably forty probe tips, most preferably 80 probe tips, or even more than 200 probe tips.

In order to properly test a variety of component packages, it is clear that individual probes of the present invention must have various probe tip pitches. Large pitches such as 1

mm or 500 um are not difficult to manufacture, but the probes of the present invention can be configured to have probe tip pitches of less than 200 um or even less than 100 um.

According to an additional feature of the present invention, a preferred configuration of the probe of the present invention, the probe tips of a probe are attached linearly along one edge of the probe body.

According to the teachings of the present invention there are provided composite probes, the composite probes being made up of a stack of substantially planar probes as described above, each of the planar probes with at least one probe tip. Each composite probe has one attachment fixture. Each of the planar probes is separated from the others by a spacer. The spacer is substantially non-conductive but is configured to allow the electronic addressing of each one of the probe tips of each one of the planar probes from the attachment fixture.

According to the teachings of the present invention there is provided a system for the testing of electronic assemblies through physical contact made up of a) at least one robotic arm with a probe-holding receptacle, each of at the least one robotic arms being independently maneuverable; b) the probe-holding receptacles configured to reversibly engage a probe and further configured to make electrical contact between an engaged probe and electronic diagnostic equipment; c). a plurality of probes, each probe independently having at least one electrically conductive probe tip; and d) a probe cassette configured to hold a plurality of the probes when the probes are not engaged by a probe-holding receptacle and the cassette further configured to present not engaged probes in such a way as to allow engagement by a probe-holding receptacle. The probes of the system of the present invention are preferably like those described herein above. The probe cassette allows many different probes, with different pitches and different numbers of probe tips to be deployed as needed by the system of the present invention.

According to a feature of the present invention the robotic arms are each independently maneuverable in an X, Y and Z direction and further, the robotic arm is configured to allow rotation of an engaged probe in a Θ coordinate.

According to a further feature of the present invention, the system includes an identification device that can identify the identity of a given probe, for example what the pitch or number of probe tips is. Such an identification device can include a mechanism configured to identify electronic characteristics of an electronic device attached to or printed on a probe, or a system that can optically read markings such as a barcode imprinted on the probe. Such

an identification device can also be an optical imaging system that includes for example a camera, to optically determine the number of probe tips or the pitch of the probe tips.

According to a further feature of the present invention, the system includes a probe diagnostic device, configured to determine the integrity of a probe. Such a device can for example be a electronic device, including for example a set of test pads, to determine that the probe and probe tips are all functioning properly. Such a device can also be based on the use of an optical imaging system to optically inspect the probe-tips to identify bent, broken or missing probe-tips.

It is advantageous to have many robotic arms to deploy many probes simultaneously. Thus a still further feature of the present invention is that it allows the use of two, four, eight, sixteen, thirty-two or more robotic arms.

It is a still further feature of the present invention of the present invention that the robotic arms and probes are configured so that two probes deployed by two separate arms can be brought very close together on the surface of the UUT, such that the probe tips of the two probes are separated by less than 10mm or even less than 5 mm.

According to the teachings of the present invention, a physical contact testing system of the present invention, substantially as described hereinabove, can be integrated into a testing system as a physical contact testing module. According to a feature of the present invention, the physical contact testing module is configured so that some of the probes are deployed to make contact with the upper surface of the UUT whereas other probes are deployed to make contact with the under-surface of the UUT. Further the system is configured so as to allow at least one arm to replace a probe while other probes maintain contact with the UUT.

According to a further feature of the present invention, the testing system is configured to provide power to at least part of the UUT. This power can be provided through the edge connector of the UUT.

According to further feature of the present invention, an optical imaging system is configured to guide the probes to make physical contact with the electronic assembly. By observing the probe tips as they approach and contact the nodes of the UUT, the optical imaging system can assist a control system to direct the probe tips to make contact with the nodes of the UUT. This allows the system to avoid the use of fiducial points and test pads, as described in the introduction hereinabove. To increase flexibility, at least part of the optical

imaging system, such as a camera can be deployed on an independently maneuverable robotic arm.

According to a further feature of the present invention, an X–ray imaging module, configured to examine the UUT using X-rays, can be added along with the physical contact testing system. According to a still further feature of the present invention there is provided an adaptable electronic assembly holder, configured to hold the UUT when being tested. The adaptable holder is configured to hold many different shapes of UUT. This holder allows many different types of UUTs to be tested using the physical contact testing module. Further, when properly configured, the adaptable holder allows the UUT to also be examined using the X-ray imaging module. According to a still further feature of the present invention there is a transport mechanism configured to automatically transfer the adaptable electronic assembly holder, when holding the UUT, between the physical contact testing module and the X-ray imaging module.

According to a further feature of the present invention, an optical imaging module, configured to optically examine the UUT, can be added along with the physical contact testing system. Elements of the optical imaging module can be contained physically in the same location as the physical contact testing module, or can be located in a physically distinct location. According to a still further feature of the present invention, in this latter case there is a transport mechanism configured to automatically transfer the adaptable electronic assembly holder, when holding the UUT, between the physical contact testing module and the optical imaging module.

The probe, the physical contact testing system and the testing system of the present invention described herein enable the use of a number of methods to test UUTs.

According to the teachings of the present invention there is provided a method for testing a UUT by: a) providing a plurality of independently addressable probe tips, each said probe tip configured to make electronic contact with a node on the UUT; b) deploying the probe tips so as to make physical contact with a plurality of nodes of the UUT; c) electronically testing the UUT a first time through said probe tips; d) redeploying at least a portion of the probe tips so as to make physical contact with a plurality of nodes of the electronic assembly; and e) electronically testing the electronic assembly a second time through said probe tips. Unique to the method of the present invention is that in either one of the tests a large number of nodes can be contacted simultaneously such as more than 25, more than 50, more than 100, more than 400 and even more than 800 nodes, depending on the

number of robotic arms and the number of probe tips on deployed probes deployed by the arms. For example, if a physical contact testing system has 16 robotic arms each deploying a probe with 50 probe tips, 800 nodes can be simultaneously contacted.

Once the probe tips are in contact with the nodes RLC parameters can be measured or an electronic signal can be applied through at least one probe tip and the response measured at the same or different nodes.

According to a further feature of the method present invention, power is provided to at least part of the UUT. This power can be provided through the edge connector of the UUT. This power can be provided, for example, by a power-supplying probe that is mounted on an independently maneuverable robotic arm.

According to the teachings of the present invention there is provided a method for testing a UUT by: a) providing a plurality of independently maneuverable arms; b) equipping at least one of the arms, each of the arms independently, with a respective first probe, each respective first probe equipped with at least one independently addressable probe tip, each probe tip configured to make electronic contact with a node of the UUT; b) deploying the probe tips using the arms so as to make physical contact with a plurality of nodes of the UUT; and c) electronically testing the UUT a first time.

A further feature of the present invention includes replacing a probe deployed on at least one of the arms, usually the probe having a different arrangement of probe tips than the first one, and then deploying the new probe so as to test the UUT a second time through a different arrangement of nodes.

As described hereinabove, the method of the present invention includes making simultaneous contact with more than 25, more than 50, more than 100, more than 400 and even more than 800 nodes, depending on the number of robotic arms and the number of probe tips on deployed probes deployed by the arms.

As described hereinabove, once the probe tips are in contact with the nodes, RLC parameters and/or electronic are measured. Power on and partial power on tests can be performed as described hereinabove.

According to the teachings of the present invention there is provided a method for testing a component attached to a UUT by: a) providing a plurality of independently maneuverable arms; b) equipping at least one of the arms, each of the arms independently, with a respective probe, each respective probe equipped with at least one independently addressable probe tip, each probe tip configured to make electronic contact with a lead of the

component being tested; c) deploying the probe tips so as to make physical contact with a plurality of leads of the component; and d) electronically testing the component. This method can be performed by a single probe deployed by a single arm, or by a plurality of probes deployed by two, four or more arms. The number of leads that are simultaneously contacted can be more than five, ten, sixty, one hundred or even more than two hundred leads. Both RLC parameters and response signals of the component can be measured. The method of the present invention can be performed by providing power to at least a portion of the electronic assembly, for example through the edge connector of the UUT as described above.

According to the teachings of the present invention there is provided a method for testing a UUT by: a) providing a plurality of independently maneuverable arms; b) equipping at least one of the arms, each arm independently, with a respective first probe, each respective first probe equipped with at least one independently addressable probe tip, each probe tip configured to make electronic contact with a node of the electronic assembly; c) deploying the probe tips using the arms so as to make physical contact with a plurality of nodes of the UUT; d) electronically testing the UUT a first time; and e) providing an automatic control system, configured to control the equipping of the arms, the deploying of the probe tips and further configured to register results of the electronic testing.

A further feature of the method of the present invention includes d) optically inspecting the UUT; and e) registering the results of the optical inspection. The automatic control system is configured to compare the electronic testing results and the optical inspection testing results. In such a way a decision can be made to reexamine parts of the UUT with one or the other inspection method. The two inspection methods support each other under the unified control of one control system. If the optical data and the electronic testing data are gathered at different physical locations, the UUT is automatically transferred between the two physical locations.

A further feature of the method of the present invention includes d) inspecting the UUT with an X-ray imaging system; and e) registering the results of the X-ray inspection. The automatic control system is configured to compare the electronic testing results and the X-ray inspection results. In such a way a decision can be made to reexamine parts of the UUT with one or the other inspection method. The two inspection methods support each other under the unified control of one control system. If the X-ray imaging data and the electronic testing data are gathered at different physical locations, the UUT is automatically transferred between the two physical locations.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention is herein described, by way of example only, with reference to the accompanying drawings, where:

FIG. 1 is a schematic representation of a testing system of the present invention;

FIG. 2A is a schematic depiction, in perspective, of an embodiment of a probe of the present invention, from the top;

FIG. 2B is a schematic depiction, in perspective, of an embodiment of a probe of the present invention, from the bottom;

FIG. 3 is a partial view of an embodiment of a probe of the present invention;

FIG. 4 is a cross-section view of an embodiment of a probe of the present invention;

FIGS. 5A to 5M are views in perspective of a variety of embodiments of a probe of the present invention;

FIG. 6 is a view, in perspective of a robotic arm of the present invention;

FIG. 7 is a cut-out view of a probe-holding receptacle;

FIGS. 8A and 8B are views, in perspective of a slide with two robotic arms of the present invention;

FIG. 8C is a view, in perspective, of a second robotic arm segment of a robotic arm of the present invention;

FIG. 9 is a schematic view from above, demonstrating how two probes of the present invention may be brought close together;

FIG. 10 is a view of an optical observation system;

FIG. 11 is a view in perspective, of an embodiment of a physical contact testing system of the present invention;

FIG. 12 is a view in perspective, of an additional embodiment of a physical contact testing system of the present invention;

FIG. 13 is a schematic depiction of a testing system of the present invention with a transport mechanism;

FIGS. 14A – 14C depict the process of holding a UUT within an adaptable holder;

FIG. 15A is a perspective view depicting a plurality of probes of the present invention deployed to make contact with active components installed on a UUT, each component having two sets of parallel leads;

FIG. 15B is a top view depicting a plurality of probes of the present invention deployed to make contact with active components installed on a UUT, each component having two sets of parallel leads;

FIG. 16A is a perspective view depicting a plurality of probes of the present invention deployed to make contact with a square-shaped component installed on a UUT having four sets of leads;

FIG. 16B is a top view depicting a plurality of probes of the present invention deployed to make contact with a square-shaped component installed on a UUT having four sets of leads; and

FIG. 17 is a perspective view of a probe holding cassette of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

The principles of the methods and operation of the probe and the testing systems according to the present invention are better understood with reference to the figures and the accompanying description. In the accompanying figures, like reference numerals refer to like parts throughout the figures.

Before turning to details of the present invention, it should be appreciated that the present invention provides a probe, a physical contact testing system, a testing system and a number of methods of testing electronic assemblies. The system of the present invention is schematically depicted in Figure 1. The system is made up of a physical contact testing module **86** able to deploy a plurality of probes, each probe with a plurality of probe tips, using independently maneuverable arms in order to test a UUT. The probes deployed by the arms are replaceable. Physical contact testing module **86** can be preferably equipped with a system **96** to optically guide the probes into contact with UUT. Physical contact testing module **86** is preferably equipped with systems such as a probe cassette **40** to hold extra probes, a system to identify probes **94**, and a system to test probe integrity **92**. AOI can be integrated into the system of the present invention either within physical contact testing module **86**, **98a**, or in a separate AOI module **98b**. X-ray imaging can be integrated as a separate module, 84. A single central control system **90** controls tests performed by physical contact testing module **86**, AOI, **98a** or **98b**, and X-ray imaging module **84**. Control system **90** is also configured to receive test results from physical contact testing module **86**, AOI, **98a** or **98b**, and X-ray imaging module **84**. Control system **90** is ideally configured to compare the results of the tests from

each module and react accordingly so that results of one module support the other. A UUT is transferable between the modules of testing system **85** using transport mechanism **78**.

The seven methods of testing electronic assemblies are: 1) a general method for testing a UUT using the probes of the present invention; 2) a method for testing individual active components on a UUT; 3) a method for testing individual components with a plurality of probes; 4) a method for improved performing of cluster and functionality tests; 5) a method for performing power-on tests; 6) a method for performing physical contact testing of a UUT coupled with another test; and 7) a method to enhance physical contact testing using AOI and X-ray inspection.

Multi-tip Probe

The probe of the present invention is a probe that due to its small dimensions and multiple tips can make simultaneous contact with many nodes on a UUT, specifically simultaneous contact with a plurality of leads of a single component.

A typical, non-limiting, embodiment of the probe of the present invention **10** is depicted in Figures 2A and 2B. A plurality of probe tips **12** are attached to a probe body **14**, made of a 0.3 mm thick fiberglass or FR-4 / G-10 glass epoxy sheet, often used in printed circuit technology. Each one of probe-tips **12** makes electric contact with one conductive path **16**. Some conductive paths **16a** (Figure 2A) pass on one side of probe body **12** and other conductive paths **16b** (Figure 2B) pass on the opposing side. All conductive paths **16** terminate near attachment end **18** of probe body **14** and are in electrical contact with one of nibs **20**. To the face of attachment end **18**, opposite nibs **20**, is attached an attachment fixture **19**, see for example Figure 5A.

In Figure 3, a detailed close-up of a probe according to the present invention is depicted. On the terminal edge of probe body **14** are printed a plurality of probe-tip contact pads **22**. Each probe-tip contact pad **22** is, for example, 2 mm long and 300 um wide. The center to center separation between any two adjacent probe-tip contact pads 22 is 500 um, corresponding to a pitch of 19.8 mil. Each probe-tip contact pad **22** is electrically connected to a respective nib **20** by a respective conductive path **16**. Each conductive path **16** is made of five substantially parallel sections. The middle section of any conductive path **16** is a 100um wide lead **24**, in electrical contact with a respective probe-tip contact pad **22**. Two 50 um wide insulator sections **26** flank lead **24**. Insulator sections **26** may be non-printed areas or printed electrical insulators or a combination thereof. Adjacent to each insulator section **26** is a 100

um wide shielding lead **28**, made of a conductive material. Shielding leads **28** are not in electrical contact with probe-tip contact pads **22**.

1 mm distant from the edge of each respective probe-tip contact pad **22**, conductive paths **16b** penetrate probe body **14** to emerge at the opposing side of probe body **14** and travel the length of probe body **12** on the opposing side, Figure 2B. Conductive paths **16b** make electrical contact with respective nibs **20b**. Conductive paths **16a** travel on only one side of probe body **14,** but pass through probe body **14** at attachment edge **18** to make electrical contact with respective nibs **20a,** Figure 2A. This crossover arrangement of conductive paths **16** helps isolate any one conductive path **16** from impedance effects from adjacent conductive paths. It is clear to one skilled in the art that the crossover arrangement allows probe **10** to be made with a fine probe-tip pitch.

Conductive paths **16** and probe-tip contact pads **22** are applied to probe body **14** using standard circuit printing technology. It is clear to one skilled in the art that, if necessary, it is also possible to construct a probe of the present invention using multi-layer circuit printing technology.

On the side of probe body **14** opposite nibs **20** is found attachment fixture **19**, see for example Figure 5A. Attachment fixture **19** allows probe **10** to be deployed by a robotic arm, as is discussed further hereinbelow.

Probe-tips **12** are commercially available gold-plated telescopic, spring-loaded probe-tips (available, for instance, from ATI Inc. in Mesa, AZ). The diameter of each probe-tip is 350 um, the distance between two mounted adjacent probe-tips is 150 um. As a result the pitch of the probe depicted in Figure 3 is 500 um. Probe-tips **12** are connected each to a respective probe-tip contact pad **22** using surface mount technology. Using spring-loaded probe-tips allows compensation for vibrations and height differences of the UUT when the probe is used.

It is clear to one skilled in the art that the probes of the present invention should be as thin as possible. At the same time, the probe body should be substantially rigid to ensure that no bending occurs, either due to thermal effect or due to pressure applied to a probe body through probe-tips contacting a UUT. In Figure 4, a side-view of a cross-section of a probe **10** according to the present invention is presented. To increase the rigidity of probe body **14,** probe body **14** is laminated after probe-tips **12** are attached. Probe body **14** is sandwiched between two 0.1 mm thick layers of Mylar (DuPont de Namours and Company, Wilmington DE) **30**, and thereafter sandwiched between two 0.3 mm thick layers of stainless steel foil **32.**

The Mylar **30** and stainless steel foil **32** layers are attached to probe body **14** using an epoxy adhesive. Beyond the probe rigidity gained by lamination, lamination also assures that probe-tips **12** are well connected to probe body **14**.

It is clear to one skilled in the art that many embodiment of the probe of the present invention as generally described above can be countenanced, both as concerns the method of construction and as concerns structure. Specifically, the pitch of the probe-tips may be higher or lower or the number of probe-tips on a probe may be varied. The highest pitch possible for a probe of the present invention is limited by the width of an individual probe-tip. The assembly of a probe of the present invention as described above is discussed to illustrate how the manufacture of a lightweight and cheap, yet rigid and effective probe can be effected.

In Figure 5, a number of embodiments of probes according to the present invention are illustrated. In Figures 5A and 5B, probes of the present invention having twelve probe tips **12** are depicted. In Figure 5C, a probe of the present invention having twenty-four probe tips **12** is depicted. In Figure 5D, a probe of the present invention having fifty-two probe tips **12** is depicted. In Figure 5E, a probe of the present invention having eighty probe tips **12** is depicted. In Figures 5F and 5G, probes of the present invention having two hundred probe tips **12** are depicted.

In Figure 5H, a probe of the present invention having seventy-two probe tips **12**, arranged in a square shape with eighteen probe tips on each side of the square is depicted. Construction of the probe based on the planar probes as described hereinabove is clear to one skilled in the art. A probe of the type such as depicted in Figure 5H is useful in contacting all the leads of a single active component.

In Figure 5I, a probe of the present invention having seventy-two probe tips **12**, arranged in a circle is depicted. Construction of the probe depicted in Figure 5I is in analogy to the construction described hereinabove clear to one skilled in the art, although it is clear that the substrate to which probe tips **12** are attached must be substantially flexible.

The planar laminated construction of the probe of the present invention as described hereinabove further allows the construction of composite probes, as depicted in Figures 5J, 5K, 5L, and 5M. To produce such a composite probe, a plurality of individual probes as described hereinabove are sandwiched together, ensuring only that conductive channels exist to allow the respective conductive channel of each probe tip **12** to be in contact with a respective nib **20**.

In Figure 5J, a composite probe of the present invention having forty probe tips **12** arrayed in two parallel rows of twenty probe tips each is depicted. In Figure 5K, a composite probe of the present invention having sixty probe tips **12** arrayed in three parallel rows of twenty probe tips each is depicted. In Figure 5L, a composite probe of the present invention having two hundred and sixty probe tips **12** arrayed in five parallel rows of fifty-two probe tips each is depicted. In Figure 5M, a composite probe of the present invention having five hundred and twenty probe tips **12** arrayed in ten parallel rows of fifty-two probe tips each is depicted.

The uses of composite probes as depicted in Figures 5J, 5K, 5L, and 5M are clear to one skilled in the art. Important to note is that such composite probes are exceptionally useful for the testing of the pad matrix on a PCB for the attachment of a ball-grid array component, before the component is installed. Using such a composite probe, all pads on the pad matrix can be contacted simultaneously.

Attachment to Robotic Arm

To use a probe **10** of the present invention, it must be attached to a maneuverable arm **34** (Figure 6) within a physical contact testing system. Arm **34** is configured to allow each one of probe-tips **12** to be independently registered through a respective conductive path (not appearing in Figure 6) by electronics measuring equipment of the testing system (see Figure 1), for instance by a shielded electrical cables based on transmission line technology, that electrically connects through a respective nib (not illustrated). Preferably arm **34** is a computer-controlled robotic arm. One skilled in the art is well acquainted with the general principles of construction and use of robotic arms. The robotic arm **34** illustrated in Figure 6 is configured to move in the X, Y and Z planes, and furthermore to rotate probe **10** perpendicularly to the UUT, by the angle Θ (around the Z-axis). Implementation of such movement is well within the ability of one skilled in the art. The Θ rotation is exceptionally important when probe **10** has a linear arrangement of probe-tips **14**.

It is possible to attach the probe of the present invention to a robotic arm to which a probe of the present invention is permanently connected, but it is preferable that the probe be easily replaceable. The fact that probe-tips are general small and fragile and yet must be used in a high-throughput environment requiring hundreds or even thousands of contact cycles in relatively short periods of times means that the tips can be easily damaged.

Due to the presence of attachment fixture **19** and nibs **20**, probe **10** depicted in Figure 2A and Figure 2B is configured to be easily replaceable "on the fly" with the use of a receptacle **36**, Figure 7, attached to the end of robotic arm **34**. Receptacle **36**, is configured to fit over attachment end **18** and attachment fixture **19** of probe **10** and hold it in place. Receptacle **36** is equipped with a piston extendible by positive air pressure **38** to press contact plate **41** against attachment end **18**. For probe **10** to be held by robotic arm **34**, the robotic arm **34** is maneuvered to position receptacle **36** over attachment end **18** of any one of the probes **10**, held within probe cassette **40**. Receptacle **36** is lowered to engulf attachment end **18** of probe **10**. Piston **38** is extended, pushing contact plate **41** to hold probe **10** in place. When release of probe **10** from receptacle **36** is desired, piston **38** is retracted, and probe **10** is released from receptacle **36**. Attachment fixture **19** is shaped so as to engage an opposing shape inside receptacle **36** and configured to strengthen attachment end **18** against the stress resulting from the pressure applied by contact plate **41** on attachment end **18**.

On contact plate **41** are found a multiplicity of contact points **42**. Contact points **42** are positioned so that when piston **38** is extended to hold probe **10** in place, each one of nibs **20** makes electrical contact with a corresponding contact point **42**. To each one of contact points **42** are connected electrically conductive leads (not illustrated) that extend from contact points **42** through the respective robotic arm to electronic diagnostic equipment which is part of the physical contact testing system.

Usually, every individual receptacle **36** which is part of a given physical contact testing system is configured to have a number of contact points **42**, equivalent to the maximum number of nibs **20** on a probe of that physical contact testing system. This number is equivalent to the maximal number of probe-tips on a probe of that physical contact testing system. For example, every receptacle of a physical contact testing system having two types of probes, one probe with ten probe-tips and another with seventy two probe tips, would have seventy two contact points. The use and factors that effect the possible variation of the number of contact points in receptacles of a physical contact testing system is clear to one skilled in the art.

There are two primary advantages for a probe of the present invention being configured to be easily replaceable on the fly. The first, as mentioned hereinabove, is that due to the relatively intense physical stress on the probe-tips, the probe-tips can be damaged. Since testing of ICBs and PCBs is preferably performed in a high throughput environment, it is desired that little or no down-time be required to replace a probe or a probe-tip which is

damaged. Furthermore, UUTs typically have many different types of components with various arrangements and pitches of component-leads. As a result testing of each type of UUT requires a different set of configurations of simultaneously contacted nodes. Since, due to considerations of space any physical contact testing system will have a finite number of robotic arms, the utility of a physical contact testing system will increased if every robotic arm is able to easily deploy many different probes with various configurations of probe-tips (in terms of, for example, number, pitch and arrangement).

In order to implement the advantages of the ease of replacement of probes as described hereinabove,.a testing system of the present invention is preferable equipped with a probe cassette **40**, Figure 1, Figure 7 and Figure 17. A probe cassette **40** is configured to hold a plurality of probes **10**. The robotic arms can access probe cassette **40** to select and engage a desired probe **10** from probe cassette **40**. Implementation of a probe cassette as used in the system of the present invention is apparent to one skilled in the art and can take the form, for example, of a tray, a carrousel, or a conveyor belt.

In order to ascertain that a probe selected from a probe cassette is the desired probe, any one of a number of methods known in the art can be employed. The probe cassette can be configured to identify and present a specific probe to the arm. Each probe can be labeled electronically or optically (*e.g.* with a bar code) which can be interrogated before or after the probe is engaged by the arm. Lastly, an optical system can be configured to examine a selected probe and determine the number, arrangement and pitch of the probe-tips of a selected probe.

It is also necessary to determine if a probe is functioning properly. There are a number of methods known in the art to determine if a probe is functioning properly. An optical system can be configured to visually examine the probe, specifically to identify broken, bent or missing probe-tips. Alternatively, a probe testing station, accessible to the robotic arms of the system, can be added to the testing system to electronically test probes. When desired, the robotic arm can engage the probe testing station with an attached probe. The probe-tips make electrical contact with testing points within probe testing station to confirm that the probe is functioning properly. It is clear to one skilled in the art, that if a testing system has probes with various geometries or probe-tip pitches, it may be necessary to supply a plurality of probe testing stations so that all probes may be electronically tested.

Multi-tip Probe Diagnostic System

It is clear to one skilled in the art that a physical contact testing system equipped with a probe as described hereinabove is most useful when a plurality of probes of the present invention can make contact with a single UUT. It is thus advantageous to provide a physical contact testing system with a plurality of robotic arms, each robotic arm equipped with a probe of the present invention, and most advantageously with probes which can be easily replaced.

The use of a plurality of probe-equipped robotic arms in a single physical contact testing system, such as flying probe systems, is well known in the art. Most often, each robotic arm is mounted on a rigid bridge, a bar that is held at two terminal points on a frame. Such a configuration has the advantage that the position of a robotic arm supported on a bridge is clearly defined, as there is little bending or flexing of the bridge, even if the robotic arm and the probe are relatively heavy.

In order to maximize the number of robotic arms in a single testing system, in one embodiment of the physical contact testing system of the present invention robotic each one of arms **34** (Figures 8A, 8B and 8C) is mounted at one point on a rail **46**. Although virtually any number of arms may be mounted on a given rail, it is most preferable to mount two robotic arms **34** on a single rail **46**, as depicted in Figures 8A and 8B. For each robotic arm **34**, a robotic arm carriage **48** is slidingly mounted to rail **46**. Robotic arm carriage **48** is configured to move along the length of rail **46** along the X-axis, and is preferably equipped with a mechanism such as an electrical DC linear motor **57** to effect this motion. Robotic arm carriage **48** is configured to hold and support a first robotic arm segment, **52**. First robotic arm segment **52** is deployed to be substantially parallel to a UUT **55** and in perpendicular to a respective rail **46**. A mechanism, such as a second electrical motor **50**, is supplied to allow first robotic arm segment **52** to move in and out in the Y-axis, perpendicularly to respective rail **46**. The motion of robotic arm carriage **48** and of first robotic arm segment **52** allow robotic arm **34** to maneuver attached probe **10** in the X-Y plane of UUT **55**.

Moveably mounted at the terminal end of first robotic arm segment **52** is a second robotic arm segment **54**, Figures 8A and 8C. Second robotic arm segment **54** is deployed substantially perpendicular to UUT **55** and substantially perpendicular to respective first robotic arm segment **52**. A mechanism, such as a third electrical motor **56**, is provided that allows second robotic arm segment **54** to move up and down, in parallel to its own axis and perpendicularly to respective rail **46**. The motion of second robotic arm segment **54** relative to

respective first robotic arm segment **52** allows robotic arm **34** to maneuver attached probe **10** move in the Z-axis of UUT **55**.

When two robotic arms **34** are mounted in pairs on a single rail **46**, as depicted in Figures 8A and 8B, robotic arm carriages **48**, first robotic arm segments **52**, and second robotic arm segments **54** are designed so that the inwards facing sides of these elements can be brought close together by ensuring that mechanisms necessary for robotic arm **34** and probe **10** functioning are deployed on the outwards facing sides of these elements.

At the terminal end of second robotic arm segment **54** is a probe-holding receptacle **36** and a Θ-rotation mechanism **58**. As described hereinabove, probe-holding receptacle **36** is configured to hold a probe **10** of the present invention. Furthermore, Θ-rotation mechanism **58**, preferably including a motor such as a fourth electrical motor **60**, is designed to rotate probe-holding receptacle **36** around an axis perpendicular to UUT **55**.

Although probe-holding receptacle **36** can be configured to hold probe **10** in a number of ways, it is most preferable that probe holding receptacle **36** be configured to hold probe **10** eccentrically, as depicted in Figure 9. As seen in Figure 9, such eccentric mounting allows two probes **10** to be brought close together. The distance between two probes **10a** and **10b** can be smaller than 10 mm or even smaller than 5 mm.

Additional details of construction of the robotic arms of the present invention are apparent to one skilled in the art from the accompanying Figures 8.

As is clear to one skilled in the art, a robotic arm of the present inventions as described hereinabove is lightweight. Similarly, the probe of the present invention as described hereinabove is lightweight. As a result the bending of the robotic arms, with the consequent uncertainty of the location of an individual probe-tip when deployed in the vicinity of a UUT is minimal. However, it is clear that it is advantageous to ensure proper probe-tip positioning by guiding the probe-tips to contact with the proper UUT nodes by using of an optical observation system. It is advantageous to mount one or more optical observation systems, each one separate robotic arm, as described hereinabove. An optical imaging system **62** installable on the robotic arms of the present invention is depicted in Figure 10. Such an optical imaging system is commercially available, for example from Watec America Corporation (Las Vegas, NV). It is important to note that an optical imaging system of a different configuration, mounted on robotic arms or not, can also be used as part of a physical contact testing system of the present invention.

An advantage of the construction of the probes and the robotic as described hereinabove is that that such a construction allows very quick acceleration, up to 0.2G yet allow a very short setting time. Thus, the unique construction as described hereinabove allows a relatively quick movement of probes to the proximity of nodes on the UUT. Such quick movement reduces the time required to perform tests when using the present invention.

When assembling a physical contact testing system **64** of the present invention, Figure 11, using robotic arms **34**, it is desirable to mount a plurality of rails **46**, each rail **46** equipped with one or more, preferably two, robotic arms **34**. Each robotic arm **34** is equipped with either an optical observation system **62** or a probe holding receptacle **36**. Rails **46** are mounted on an inspection frame **66** in various combinations. In the embodiment depicted in Figure 11, twelve individual rails **46** are mounted on inspection frame **66**. Six rails **46** are mounted so as to allow respective robotic arms **34** to maneuver above a UUT **55** and six rails **46** are mounted so as to allow respective robotic arms to maneuver below UUT **55**. As is clear to one skilled in the art, different numbers of rails **46** can be mounted on inspection frame **66** above and below UUT **55** depending on the applications for which a specific testing system of the present invention is designed. If both the top and the bottom side of UUT **55** are each to be serviced by two optical observation systems (not illustrated in Figure 11) attached to robotic arms **34**, then in the case of the embodiment of the testing system **64** depicted in Figure 11, twenty two independently maneuverable probes **10** of the present invention can be directed to make simultaneous contact with UUT **55**.

Additional details of construction of a rigid frame and attaching robotic arms of the present invention thereto are apparent to one skilled in the art from the accompanying Figure 11 and Figure 12. In Figure 12, an additional embodiment of a physical contact testing system **68** of the present invention is depicted where a total of eight probes **10** can contact a UUT **55**, with the use of four robotic arms **34** from the top and four robotic arms **34** from below.

UUT holder

Some flying probe testing systems known in the art are configured to contact nodes on either side of the UUT. This is done by producing a customized fixture that can snugly hold a UUT of a specific shape in a fixed position by making contact with the periphery of the UUT. Each of the various types of UUTs expected to be tested by the system must have a customized fixture. This prevents existing flying probe testing systems from testing UUTs with unexpected shapes.

A testing system **70**, Figure 13, of the present invention is preferably equipped with an adaptable holder **72**. Adaptable holder **72** has a rigid holder frame **74** having transport elements **76** configured to engage a transport mechanism **78**, such as a system of transport rails, to move UUT **55** into testing system **70** and between different modules, **84** and **86**, of testing system **70**. The internal dimensions of holder frame **74** are sufficiently large to accommodate the largest UUT to be tested by testing system **70**. Around the periphery of holder frame **74** are deployed a plurality of independently extendible holder arms **80**, tipped with clamps **82**. Clamps **82** are configured to hold UUT **55** without damaging UUT **55**.

In preparation for testing a UUT **55** using a testing system of the present invention, UUT **55** is positioned within holder frame **74**, Figure 14. Holder arms **80** are extended so that the edges of UUT **55** are positioned within clamps **82**. Clamps **82** are closed to hold UUT **55** in place, and holder frame **74**, along with UUT **55**, is transported into testing system **70** by transport mechanism **78**.

Clamps **82** are preferably biased to a closed position with a force that is known not to damage UUT **55** to ensure that in the case of power failure UUT **55** is not released from holder frame **74**. The extent of extension of extendible arms **80** can be controlled in a variety of ways known to one skilled in the art, for instance through the use of an optical imaging system or by pressure-sensitive detectors, positioned between the opposing elements of the clamps.

When probes of the present invention make contact with a UUT held within an adaptable holder of the present invention, the UUT may flex due to the pressure applied by the probes. Such flexing causes the absolute location of components or nodes to become ill-defined. Thus, when using an adaptable holder of the present invention, it is most preferable to control landing of probes with the help of an optical imaging system as described hereinbelow, to compensate for the uncertainty in node location caused by UUT flexing.

Adaptable holder **72** of the present invention as described hereinabove can also be used to hold UUT **55** in position when examined through the use of an X-ray imaging module **84**, Figure 13. Since UUT **55** is held only at the edges, X-rays may be projected from either the top or the bottom without any parts of adaptable holder **72** obstructing the travel of X-rays through the UUT **55** to an X-ray detector. It is thus possible to add an X-ray imaging module **84** to a testing system **70** of the present invention, alongside a physical contact testing module **86** configured to deploy probes of the present invention. If there are no space limitations, the X-ray imaging module may be integrated into the same package as other modules of the

testing system. However, since X-ray imaging systems require bulky shielding, it is preferable that an X-ray imaging module that is part of a testing system of the present invention be added in a package physically separate from other elements of the diagnostic system, as depicted in Figure 13. Transport mechanism **78** is configured to transport adaptable holder **72** with UUT **55** therein between X-ray imaging module **84** and physical contact testing module **86** of testing system **70**.

Direct integration of an X-ray imaging system with a physical contact testing system deploying the probes of the present invention as described above allows a UUT to be tested more quickly and thoroughly than known in the art heretofore. This is especially true when a single unified control system is configured to control both the X-ray imaging and the physical contact testing system, and the testing system has the means to transport a UUT between the two modules automatically.

As is clear to one skilled in the art and from the description hereinabove a testing system of the present invention can be constructed with many different variations and options. In Figure 1, a schematic diagram of the various elements which make up the embodiments of a system **85** of the present invention are presented. The most basic embodiment includes a physical contact testing module **86**, operatively associated with electronic diagnostic instrumentation **88** and a control system **90**. Accessible to the robotic arms of physical contact testing module **86** is preferably one or more probe cassettes **40**, one or more probe testing devices **92**, and one or more probe identification devices **94**. It is also preferable to include an optical probe guidance device **96**. The optical probe guidance device **96** can be configured to perform AOI. It is also possible to include a separate AOI device **98** within the physical contact testing module **86** package. To system **85**, an X-ray imaging module **84** and an AOI module **86** can also be added. Preferably, all modules are controlled by a single control system **90**. Preferably a UUT is transferable between the modules of testing system **85** using transport mechanism **78**.

Methods of Testing a UUT

A number of testing methods employing physical contact can be employed to test a UUT using a testing system of the present invention as described hereinabove.

General method for testing a UUT

After the UUT is contained within the physical contact testing system of the present invention, a first step is to determine a test protocol either through preprogramming by a person, or automatically by a control system based on a description of the UUT topology (for instance, from a CAD system). The test protocol is made up of a series of probe contact configurations. Each probe contact configuration consists of a number of probes of the present invention deployed to be in contact with nodes of the UUT. Once the test protocol has been determined, it can be applied.

For each contact configuration the proper probes are taken from the probe cassette and attached to the robotic arms, during an equipment step. If necessary, the probes are tested or examined to ensure proper functioning.

Following the equipment step is the positioning step. The robotic arms position the probes to make contact with the designated nodes of the UUT. This is preferably done by first moving a robotic arm to an approximate location based on an estimated location of the nodes. Once a probe is in an approximate location, the probe-tips of the probe are brought into contact with the nodes with the help of an optical observation system.

Methods that can be applied with suitable modification for guiding the probe-tips of the present invention to contact with nodes of a UUT have been described in US Patents 5,394,100 and 5,644,245. Optical guidance for contact allows a soft landing to reduce probe-tip damage and compensates for discrepancies in UUT topology resulting from manufacturing inaccuracies as described hereinabove. Furthermore, optical guidance allows the tolerances of the manufacture of the elements of the physical contact testing system to be relaxed.

Once all probes have been positioned, electronic tests are performed in the testing step. Since the probes of the present invention and the large number of robotic arms of the physical contact testing system of the present invention allow many nodes to be contacted simultaneously, a very large number of electronic tests is performed after each positioning step.

In some cases it may be possible, due to the large number of UUT nodes that may be simultaneously contacted, to perform all desired electronic tests with one contact configuration. If not, the following contact configuration in the series making up the testing protocol is performed, as described above.

Due to the large number of nodes simultaneously contacted by the physical contact testing system of the present invention, testing using the physical contact testing system is a significant qualitative improvement when compared to testing using flying probe systems.

Method for testing individual components

The use of the physical contact testing system of the present invention allows the testing of individual components mounted on a UUT, specifically of active components having many leads. Although prior art flying probe testing systems can rigorously test passive components with two or three leads, such as capacitors or resistors, these flying probe testing systems do not have a sufficient number of probe-tips to make contact with enough leads to rigorously test an active component. ICT systems can be used to perform rigorous testing, but require test pads and a dedicated fixture for each UUT.

By deploying one or more probes of the present invention, an active component can be rigorously tested by deploying one or more robotic arms equipped with probes so that all necessary component-leads are simultaneously contacted. This can be done by providing a single probe of the present invention that has a specific arrangement of probe-tips so that the single probe can be used to make contact with all the required leads of the component. Such a probe can be fashioned, for example, with the appropriate modifications as described hereinabove.

Method for testing individual components with a plurality of probes

According to a further method of the present invention, two or more probes of the present invention are deployed to make contact with all the leads of a component necessary for rigorous testing.

Some active components **100** are produced having two sets of substantially parallel leads **102a** and **102b** extending along opposite sides of the package, Figure 15A and 15B. Two probes **10** of the present invention are deployed in parallel, one on each side of component **100** to make contact with all leads **102** necessary to perform a rigorous test. It is preferable that each of probes **10** has a number of probe-tips **12** identical to the number of leads **102a** on a respective side of component **100**, and that the pitch of probe-tips **12** be identical to the pitch of leads **102** of active component **100**. However, as is clear to one skilled in the art, this restriction is not stringent. For example, a probe with a number of probe-tips

greater than the number of leads on a respective side of a component being tested can also be used.

As can be seen from Figure 9, if probes **10** are mounted eccentrically in receptacles **36** as described hereinabove, two probes **10** can be brought very close together. Thus, the method of the present invention can be used to effectively test an active component with two sets of substantially parallel leads **102** wherein the width of component **100** is as little as 10.0 mm, or even 5.0 mm.

Active components are also often produced having a plurality of sets of leads, each set extending along a side of the periphery of the component. Most often such a component **104** is square or rectangular in shape, Figures 16A and 16B. In such a case, four probes **10a, 10b, 10c** and **10d** are deployed, one on each side of component **104** to make contact with all leads **106a, 106b, 106c** and **106d**, respectively, necessary to perform a rigorous test.

As can be seen from Figures 16A and 16B, it is often necessary that probes **10** be interleaved to allow contact with all leads **106a, 106b, 106c** and **106d** of component **104**. In Figures 16A and 16B is demonstrated a specific and common situation where four probes **10** are interleaved around a square shaped component **104**. In the situation depicted in Figures 16A and 16B, each side of component **104** has an identical number of leads with an identical pitch. As a result four different types of probes **10** are deployed: tall left-handed **10a**, tall right-handed **10b**, short left-handed **10c** and short right-handed **10d**. It is clear to one skilled in the art, that when probes **10** are not mounted eccentrically in receptacles **36**, there is no practical effect to the handedness of probes **10**. The issue of "tall" and "short" probes can be more clearly understood by comparing the two probes with twelve probe tips each depicted in Figure 5A and 5B or the two probes with two hundred probe tips each depicted in Figure 5F and 5G.

As can be seen from Figures 16, probes **10** of the present invention can be used to test an active component with four sets of leads arrayed around the periphery of a component, wherein the narrow dimension of the component is as little as 26 mm, or even 5.0 mm.

It is clear to one skilled in the art that, with the appropriate modifications, the method as described hereinabove can be used to test components with other configurations and arrangements of component-leads. Such arrangements include but are not limited to components with three sets of leads arrayed around a triangular component, six sets of leads arrayed around a hexagonal component, or two sets of interleaved leads.

Method for improved performance of cluster and functionality tests

Another method of the present invention is the performance of a cluster or functionality test. As described in the introduction hereinabove, cluster and functionality tests require that multiple of nodes be contacted simultaneously. Existing flying probe diagnostic systems have a number of probe-tips sufficient to make contact with only a limited number of nodes, and thus can perform cluster and functionality tests with only limited effectiveness. ICT systems are used, but require test pads and a customized fixture for each UUT.

Using a physical contact testing system of the present invention, a cluster or functionality test may be performed through direct contact with component-leads as well as through printed test pads. As a first step, the appropriate probes are selected and deployed so that the probe-tips contact all the required nodes. Once contact is made, the cluster or functionality tests are performed as described in the art.

An advantage of the method of the present invention is that after one such test has been performed, a following additional cluster test can be performed. In the art, a cluster or functionality test determines only whether or not a predetermined cluster of components or a set of functions is performs properly. A cluster is delineated by the availability of accessible nodes. According to the method of the present invention, following testing of one cluster, a different set of probes can be deployed to examine a sub-cluster or sub-group of components. In such a way, if a cluster is determined to function improperly, it can be divided into separate subclusters, each of which can then be separately interrogated.

Method for performing Power-On Tests

In the testing systems known in the art, power-on, UUT functionality and boundary scan tests are performed through the edge-connector of the UUT, using a special adapter that is manually attached to the UUT. Such tests can be performed with greater ease using the physical contact testing system of the present invention. A specially designed probe is supplied, configured to make contact with the individual leads of the edge connector. As the leads of the edge connector are most often relatively large compared to the size of the leads of the components, the probe-tips and the conducting leads of a probe provided for contacting the edge-connector can be configured to carry the current required when performing a power-on test. During or following other tests performed by the physical contact system of the present invention, the edge-connector probe is deployed to make electrical contact with the edge-connector of the UUT. Current is transferred through the edge-connector probe, which

also performs the required functionality and boundary scan tests. Simultaneously, additional probes can be deployed to make contact with nodes on the UUT when required.

As described hereinabove, power-on tests may damage good components when a fault is present elsewhere on the UUT. Thus, it is most preferable to first perform a complete set of power-off tests, followed by a power-on test as described hereinabove.

Method for testing a UUT coupled with another testing method

As described in the introduction hereinabove, PCBs can be tested using physical contact testing, AOI or X-ray imaging. These methods all give complementary information concerning the UUT. In the art, X-ray imaging techniques are not directly coupled to other testing devices as described above. It is clear to one skilled in the art that it would be exceptionally advantageous to have an integrated system combining physical contact testing with X-ray imaging and AOI testing. Although transferring a UUT from one testing system to another manually can be done, it is preferable that such a transfer be done automatically. Furthermore, it would be advantageous that these separate systems communicate, allowing faults discovered by one testing system to be re-examined by another

A further method of the present invention is to use the testing system of the present invention, configured with the physical contact testing system of the present invention as one module and at least one additional module implementing a different testing method. A UUT is placed within an adaptable holder and automatically transferred from one module to another using a transport mechanism.

Once one module identifies a fault on the UUT, the control system can decide to examine the fault or components that may be related to the fault using a complementary testing system.

Method to enhance physical contact testing Using AOI

An AOI system can be used to enhance the effectivity of the physical contact testing system, if contained within the same module. After a probe has made contact with a UUT and an improper response is registered, the optical observation system is deployed to inspect if there is any apparent damage or missing component, or if the electrical contact between the probe-tip and the node is insufficient. If the probe-tip does not make proper contact with the node, the probe-tip is redeployed and the test is repeated.

The teachings of the present invention can be applied to many different electronic assemblies but the primary intended application as described herein concerns the inspection of UUTs such as populated and unpopulated circuit boards, ICB and PCB respectively. It is clear to one skilled in the art that the present invention is not limited to the embodiments described herein but also relates to all kinds of modifications thereof, insofar as they are within the scope of the claims.

WHAT IS CLAIMED IS:

1. A probe for the testing of electronic assemblies comprising:

   a. a non-conductive probe body;

   b. at least two conductive probe tips rigidly attached to said probe body; and

   c. for each said probe tip, a respective conductive channel in electrical contact with said each probe tip, where each said conductive channel is electrically isolated from other said conductive channel.

2. The probe of claim 1 wherein said probe body is laminated.

3. The probe of claim 2 wherein said probe body is substantially planar.

4. The probe body of claim 3 wherein said probe body with said lamination is less than 5.0 mm thick.

5. The probe body of claim 4 wherein said probe body with said lamination is less than 3.0 mm thick.

6. The probe body of claim 5 wherein said probe body with said lamination is less than 1.5 mm thick.

7. The probe body of claim 6 wherein said probe body with said lamination is less than 1.3 mm thick.

8. The probe of claim 1 wherein there are at least five probe tips rigidly attached to said probe body.

9. The probe of claim 8 wherein there are at least ten probe tips rigidly attached to said probe body.

10. The probe of claim 9 wherein there are at least twenty probe tips rigidly attached to said probe body.

11. The probe of claim 10 wherein there are at least forty probe tips rigidly attached to said probe body.

12. The probe of claim 11 wherein there are at least eighty probe tips rigidly attached to said probe body.

13. The probe of claim 12 wherein there are at least two hundred probe tips rigidly attached to said probe body.

14. The probe of claim 1 wherein said probe tips are attached to said probe body with a pitch of less than 1 mm.

15. The probe of claim 14 wherein said probe tips are attached to said probe body with a pitch of less than 500 um.

16. The probe of claim 15 wherein said probe tips are attached to said probe body with a pitch of less than 200 um.

17. The probe of claim 16 wherein said probe tips are attached to said probe body with a pitch of less than 100 um.

18. The probe of claim 1wherein said probe tips are attached in a single row along an edge of said probe body.

19. The probe of claim 1 wherein each said probe tip is independently registerable by electronic measuring instrumentation.

20. The probe of claim 1 wherein each said probe tip is spring loaded.

21. The probe of claim 1 wherein said conductive channels are printed onto said probe body.

22. The probe of claim 1 wherein each of said conductive channels is electrically shielded.

23. A system for the testing of electronic assemblies through physical contact comprising:

a. at least one robotic arm with a probe-holding receptacle, each of said at least one robotic arms being independently maneuverable;

b. a plurality of probes, each said probe independently having at least one electrically conductive probe tip;

c. said probe-holding receptacle configured to reversibly engage one of said probes and further configured to make electrical contact between said engaged probe and electronic diagnostic equipment; and

d. a probe cassette configured to hold a plurality of said probes when said probes are not engaged by a said probe-holding receptacle and further configured to present said not-engaged probes to allow engagement by a said probe-holding receptacle.

24. The system of claim 23 wherein each said robotic arm is independently maneuverable in an X, Y and Z direction.

25. The system of claim 23 wherein each said robotic arm is configured to allow rotation of said engaged probe in a Θ coordinate.

26. The system of claim 23 further comprising

e. an identification device configured to identify an arrangement of said probe tips of a said probe.

27. The system of claim 26 wherein said identification device includes a mechanism configured to identify an electronic circuit attached to a said probe.

28. The systems of claim 26 wherein said identification device includes a mechanism configured to optically identify a symbol imprinted on said probe.

29. The system of claim 28 wherein said symbol is a barcode.

30. The systems of claim 26 wherein said identification device includes a mechanism configured to optically identify a number of said probe tips of a said probe.

31. The systems of claim 26 wherein said identification device includes a mechanism configured to optically identify a pitch of said probe tips of a said probe.

32. The system of claim 23 further comprising

e. a probe diagnostic device configured to determine integrity of a said probe.

33. The system of claim 32 wherein said probe diagnostic device includes a mechanism configured to form an electronic circuit through said probe tips of a said probe.

34. The systems of claim 32 wherein said probe diagnostic device includes a mechanism configured to optically examine said probe tips of a said probe.

35. The testing system of claim 23 with at least two said robotic arms.

36. The testing system of claim 35 with at least four said robotic arms.

37. The testing system of claim 36 with at least eight said robotic arms.

38. The testing system of claim 37 with at least sixteen said robotic arms.

39. The testing system of claim 38 with at least thirty-two said robotic arms.

40. The testing system of claim 35 wherein at least two of said at least four said robotic arms and respective said probe-holding receptacles are configured to bring two engaged said probes to a separation of less than 10 mm.

41. The testing system of claim 40 wherein said separation is less than 5 mm.

42. A testing system for testing an electronic assembly with a top side and a bottom side comprising a physical contact testing module, said physical contact testing module having:

a. at least two independently maneuverable arms, each said arm configured to deploy a respective probe; and

b. each said probe, independently having at least two attached probe tips;

and wherein said arms and said probes are configured so as to allow simultaneous physical contact of said probe tips of a plurality of said probes with the electronic assembly.

43. The testing system of claim 42 wherein each said arm is independently maneuverable in an X, Y and Z direction.

44. The testing system of claim 42 wherein each said arm is configured to allow rotation of said respective probe in a Θ coordinate.

45. The testing system of claim 42 wherein said arms and said probes are further configured to allow simultaneous contact of a first plurality of said probe tips with the top side of the electronic assembly and of a second plurality of said probe tips with the bottom side of the electronic assembly.

46. The testing system of claim 42 with at least four said independently maneuverable arms.

47. The testing system of claim 46 with at least eight said independently maneuverable arms.

48. The testing system of claim 47 with at least sixteen said independently maneuverable arms.

49. The testing system of claim 48 with at least twenty said independently maneuverable arms.

50. The testing system of claim 49 with at least thirty-two said independently maneuverable arms.

51. The testing system of claim 42 wherein said arms are configured so that at least one of said arms can replace a said respective said probe while at least one respective probe of another of said arms is in contact with the electronic assembly.

52. The testing system of claim 42 wherein each said probe tip of a said probe is independently registerable by electronic diagnostic instrumentation when said probe is deployed by a said arm.

53. The testing system of claim 42 further comprising:

c. an optical imaging system configured to guide said probes to make physical contact with the electronic assembly.

54. The testing system of claim 53 wherein at least one said robotic arm is configured to deploy at least a part of said optical imaging system.

55. The testing system of claim 42 further comprising an X-ray imaging module configured to examine the electronic assembly using X-ray imaging.

56. The testing system of claim 55 further comprising:

an adaptable electronic assembly holder, configured to hold the electronic assembly when being tested, said adaptable holder configured to hold a plurality of shapes of electronic assemblies.

57. The testing system of claim 56 further comprising a transport mechanism to automatically transfer said adaptable electronic assembly holder between said physical contact testing module and said X-ray imaging module.

58. The testing system of claim 42 further comprising an optical inspection module configured to optically inspect the electronic assembly.

59. The testing system of claim 58 further comprising an adaptable electronic assembly holder, configured to hold the electronic assembly when being tested, said adaptable holder configured to hold a plurality of shapes of electronic assemblies.

60. The testing system of claim 59 further comprising a transport mechanism to automatically transfer said adaptable electronic assembly holder between said physical contact testing module and said optical inspection module.

61. The testing system of claim 42 further configured to provide power to at least a portion of the electronic assembly.

62. The testing system of claim 61 configured to provide power through an edge connector of the electronic assembly.

63. The testing system of claim 62 wherein said power is provided through an edge connector of the electronic assembly by a power-supplying probe with a plurality of probe tips, said probe tips configured to supply power through the edge connector, said power-supplying probe deployed to make contact with said edge connector by an independently maneuverable arm.

64. A method for testing an electronic assembly comprising:

a. providing a plurality of independently addressable probe tips, each said probe tip configured to make electronic contact with a node;

b. deploying said probe tips so as to make physical contact with a plurality of nodes of the electronic assembly;

c. electronically testing the electronic assembly a first time through said probe tips;

d. redeploying at least a portion of said probe tips so as to make physical contact with a plurality of nodes of the electronic assembly; and

e. electronically testing the electronic assembly a second time through said probe tips.

65. The method of claim 64 wherein said plurality of probe tips includes at least twenty five probe tips.

66. The method of claim 65 wherein said plurality of probe tips includes at least fifty probe tips.

67. The method of claim 67 wherein said plurality of probe tips includes at least one hundred probe tips.

68. The method of claim 68 wherein said plurality of probe tips includes at least four hundred probe tips.

69. The method of claim 68 wherein said plurality of probe tips includes at least eight hundred probe tips.

70. The method of claim 64 wherein said electronic testing includes measuring RLC parameters.

71. The method of claim 64 wherein said electronic testing includes applying an electronic signal through at least one of said probe tips and measuring at least one response signal through at least one other of said probe tips.

72. The method of claim 71 further comprising providing power to at least a portion of the electronic assembly.

73. The method of claim 72 wherein said power is provided through an edge connector of the electronic assembly.

74. The method of claim 73 wherein said power is provided through a edge connector of the electronic assembly by a power-supplying probe with a plurality of probe tips, said probe tips configured to supply power through the edge connector, said power-supplying probe deployed to make contact with said edge connector by an independently maneuverable arm.

75. The method of claim 64, wherein said deploying of said probe tips is in a first configuration, and wherein said redeploying of said at least portion of said probe tips is in a second configuration different from said first configuration.

76. A method for testing an electronic assembly comprising:

a. providing a plurality of independently maneuverable arms;

b. equipping at least one of said arms with a respective first probe, each respective said first probe equipped with at least one independently addressable probe tip, each said probe tip configured to make electronic contact with a node of the electronic assembly;

c. deploying said probe tips using said arms so as to make physical contact with a plurality of nodes of the electronic assembly; and

d. electronically testing the electronic assembly a first time through said probe tips.

77. The method of claim 76 further comprising

e. re-equipping at least one of said arms with a respective second probe, said second probe having a plurality of independently addressable probe tips arranged differently thereon than said probe tips of said first probe;

f. redeploying at least a portion of said probe tips so as to make physical contact with a plurality of nodes of the electronic assembly; and

g. electronically testing the electronic assembly a second time through said probe tips.

78. The method of claim 76 wherein a number of probe tips deployed includes at least twenty-five probe tips.

79. The method of claim 78 wherein a number of probe tips deployed includes at least fifty probe tips.

80. The method of claim 79 wherein a number of probe tips deployed includes at least one-hundred probe tips.

81. The method of claim 80 wherein a number of probe tips deployed includes at least four-hundred probe tips.

82. The method of claim 81 wherein a number of probe tips deployed includes at least eight-hundred probe tips.

83. The method of claim 76 further wherein said electronic testing includes measuring RLC parameters.

84. The method of claim 76 further wherein said electronic testing includes applying an electronic signal through at least one of said probe tips and measuring at least one response signal through at least on other of said probe tips.

85. The method of claim 76 further comprising providing power to at least a portion of the electronic assembly.

86. The method of claim 85 further wherein said power is provided through a edge connector of the electronic assembly.

87. The method of claim 86 further wherein said power is provided through an edge connector of the electronic assembly by a power-supplying probe with a plurality of probe tips, said probe tips configured to supply power through the edge connector, said power-supplying probe deployed to make contact with said edge connector by an independently maneuverable arm.

88. The method of claim 76 wherein said equipping of said arms is performed for each of said arms independently.

89. A method for testing a component attached to an electronic assembly comprising

a. providing a plurality of independently maneuverable arms;

b. equipping at least one of said arms with a respective probe, each respective said probe equipped with at least one independently addressable probe tip, each said probe tip configured to make electronic contact with a lead of the component;

c. deploying said probe tips using said arms so as to make physical contact with a plurality of said leads of the component; and

d. electronically testing the component a through said probe tips.

90. The method of claim 89 wherein said plurality of arms includes at least two arms.

91. The method of claim 90 wherein said plurality of arms includes at least four arms.

92. The method of claim 89 wherein said plurality of leads includes at least five leads.

93. The method of claim 92 wherein said plurality of leads includes at least ten leads.

94. The method of claim 93 wherein said plurality of leads includes at least sixty leads.

95. The method of claim 94 wherein said plurality of leads includes at least one hundred leads.

96. The method of claim 95 wherein said plurality of leads includes at least two hundred leads.

97. The method of claim 89 wherein said electronic testing includes measuring RLC parameters.

98. The method of claim 89 wherein said electronic testing includes applying an electronic signal through at least one of said probe tips and measuring at least one response signal through at least on other of said probe tips.

99. The method of claim 89 further comprising providing power to at least a portion of the electronic assembly.

100. The method of claim 99 wherein said power is provided through a edge connector of the electronic assembly.

101. The method of claim 100 wherein said power is provided through a edge connector of the electronic assembly by a power-supplying probe with a plurality of probe tips, said probe tips configured to supply power through the edge connector, said power-supplying probe deployed to make contact with said edge connector by an independently maneuverable arm.

102. The method of claim 89 wherein said equipping of said arms is performed for each of said arms independently.

103. A method for testing an electronic assembly comprising:

a. providing a plurality of independently maneuverable arms;

b. equipping at least one of said arms, with a respective first probe, each respective said first probe equipped with at least one independently addressable probe tip, each said probe tip configured to make electronic contact with a node of the electronic assembly;

c. deploying said probe tips using said arms so as to make physical contact with a plurality of nodes of the electronic assembly; and

d. electronically testing the electronic assembly a first time through said probe tips; and

e. providing an automatic control system, configured to control said equipping of said arms, said deploying of said probe tips and further configured to register electronic testing results of said electronic testing.

104. The method of claim 103 further comprising:

d. optically inspecting said electronic assembly; and

e. registering optical inspection testing results of said electronic testing

wherein said automatic control system is further configured to compare said electronic testing results and said optical inspection testing results.

105. The method of claim 104 wherein the electronic assembly is automatically transferred between a first location wherein said electronic testing occurs and a second location wherein said optical inspection occurs.

106. The method of claim 103 further comprising:

d. inspecting said electronic assembly using X-ray imaging; and

e. registering X-ray inspection testing results of said electronic testing

wherein said automatic control system is further configured to compare said electronic testing results and said X-ray testing results.

107. The method of claim 106 wherein the electronic assembly is automatically transferred between a first location wherein said electronic testing occurs and a second location wherein said X-ray inspection occurs.

108. The method of claim 103 wherein said equipping of said arms is performed for each of said arms independently.

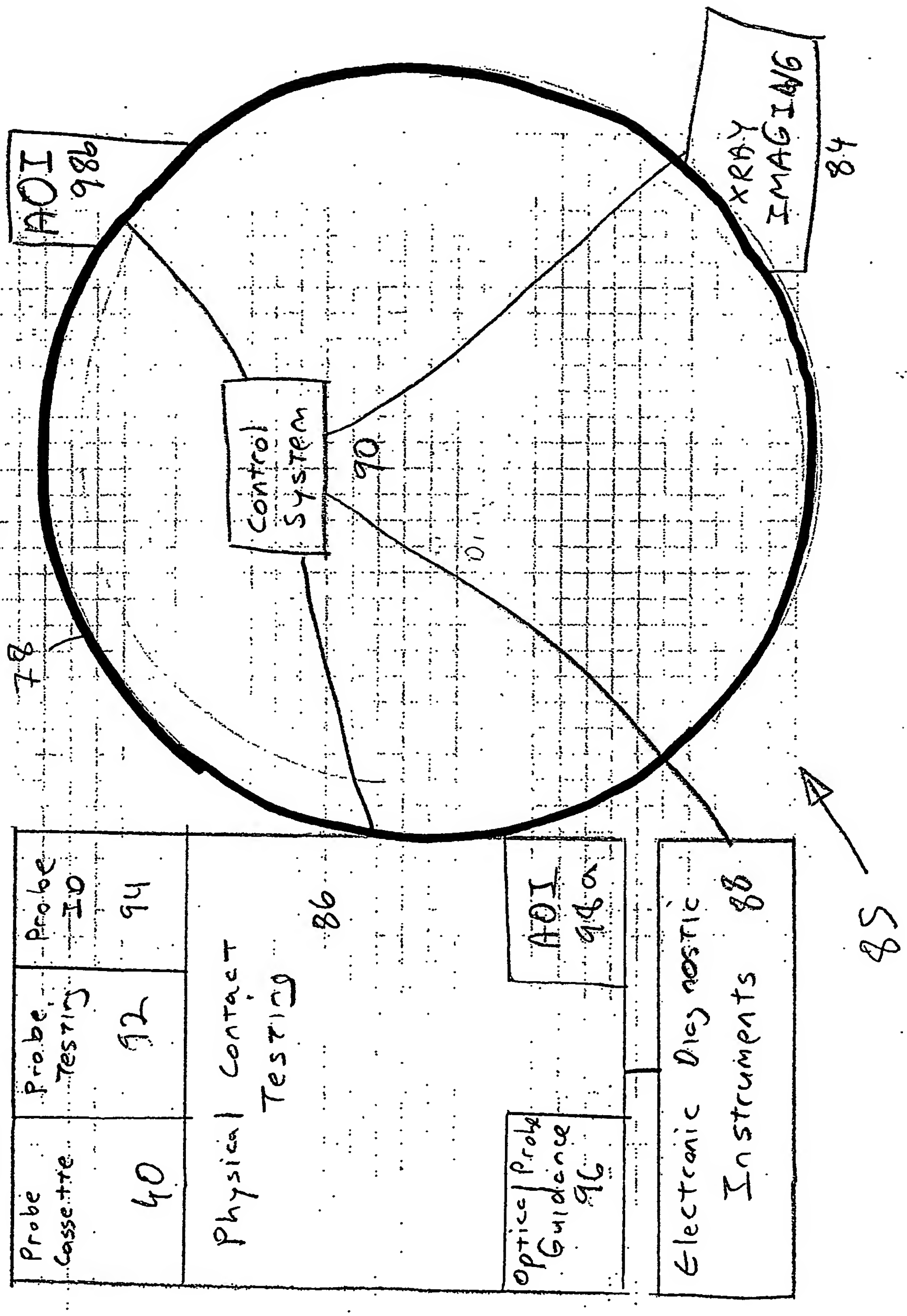

Probe Cassette
40
Probe Testing
92
Probe ID
94
Physical Contact Testing
86
AOI
98a
Optical Probe Guidance
96
Electronic Diagnostic Instruments
88
Control System
90
AOI
98b
XRAY IMAGING
84
78
85

FIGURE 1

FIGURE 2

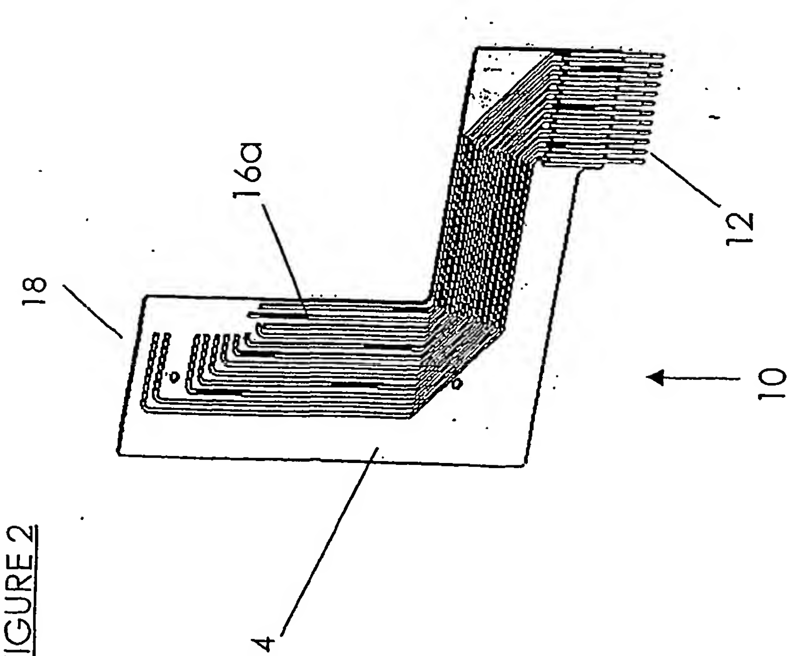


FIGURE 2A

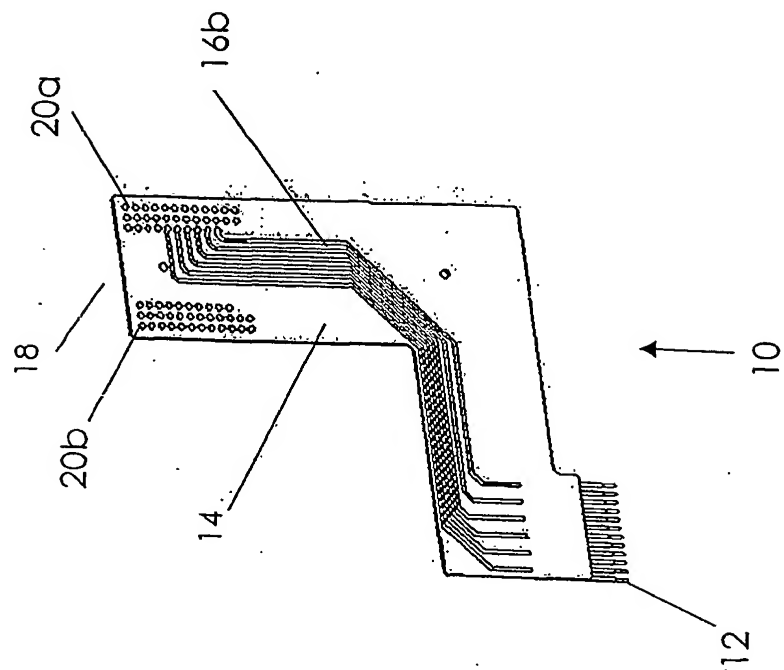


FIGURE 2B

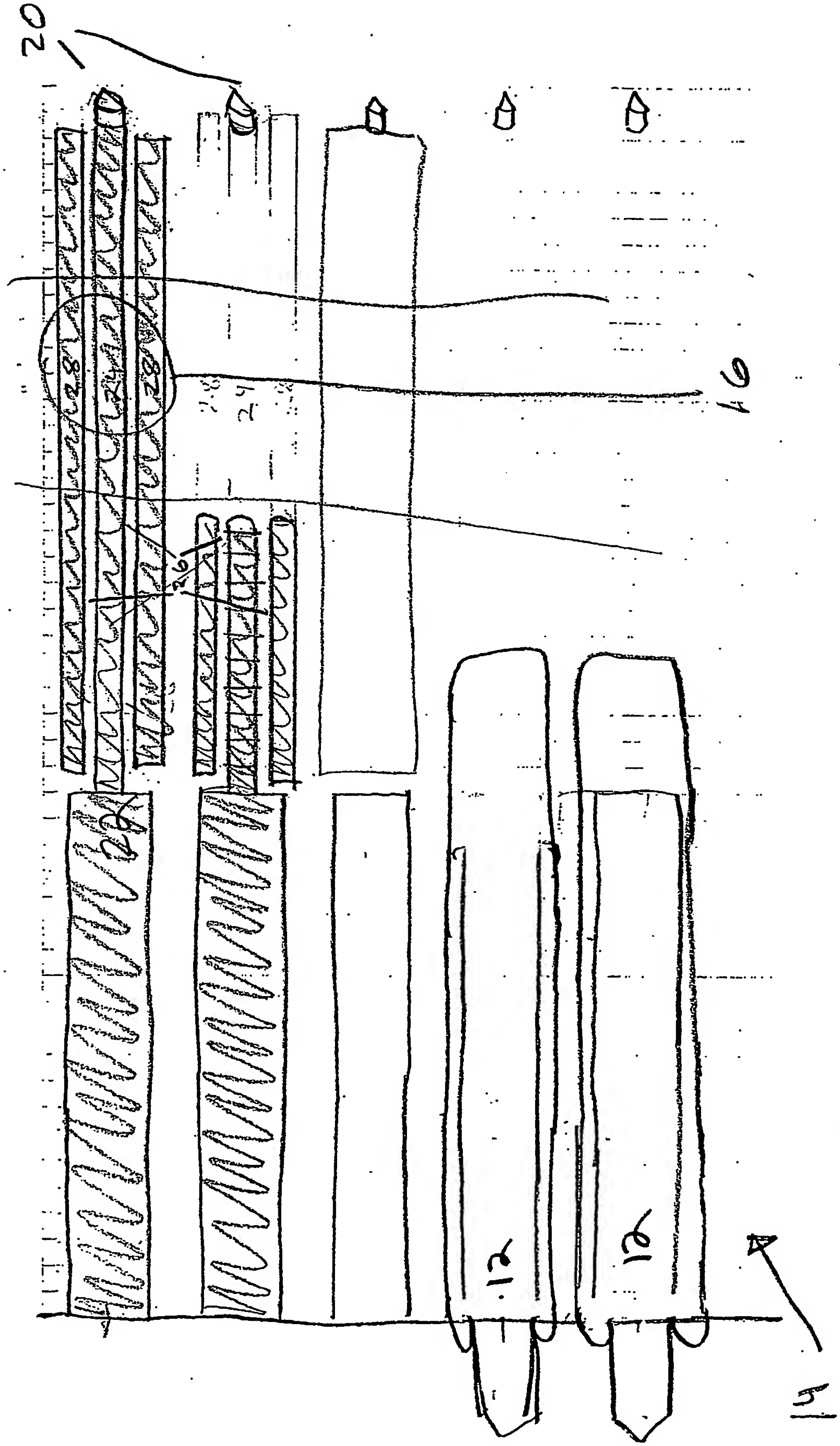
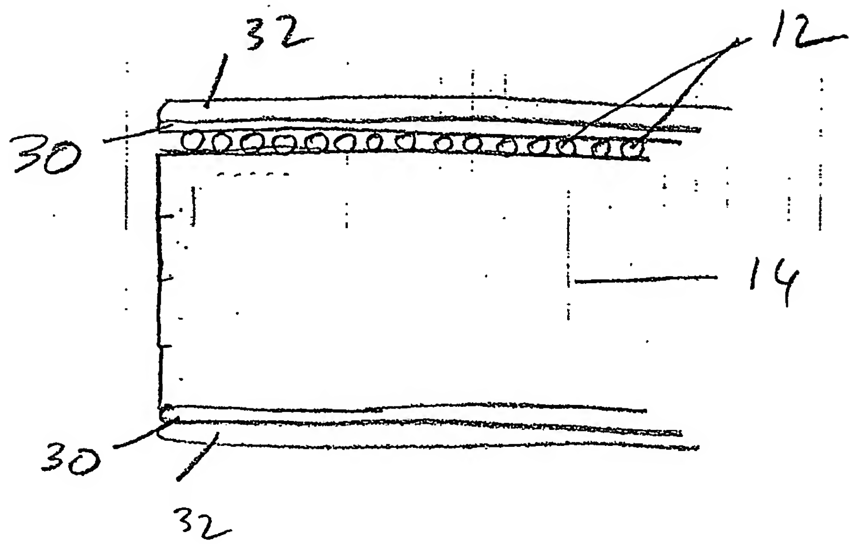


FIGURE 3

Figure 4



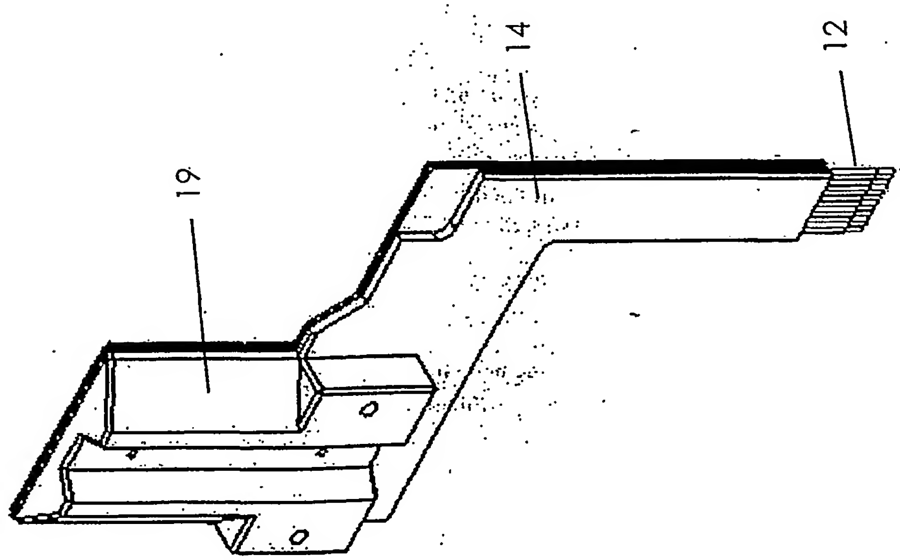


FIGURE 5A

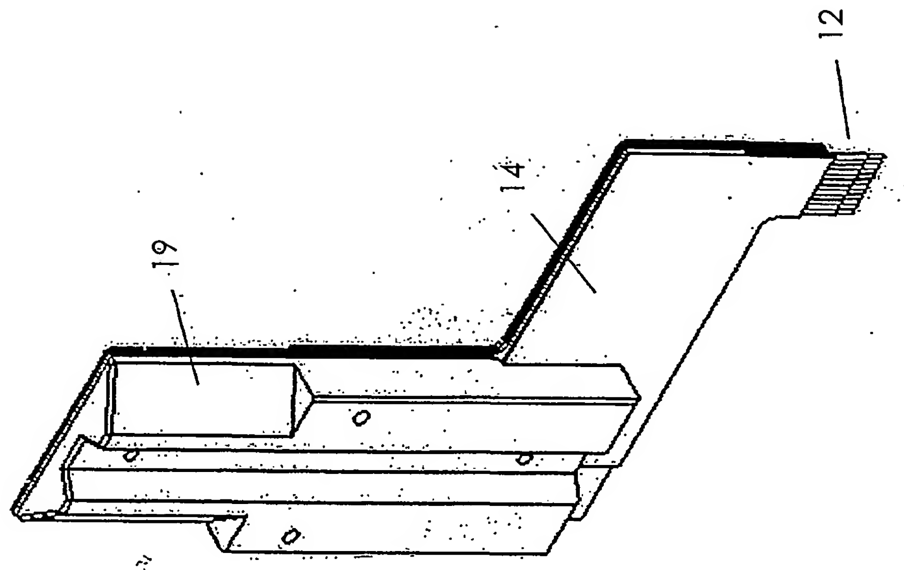


FIGURE 5B

FIGURE 5D

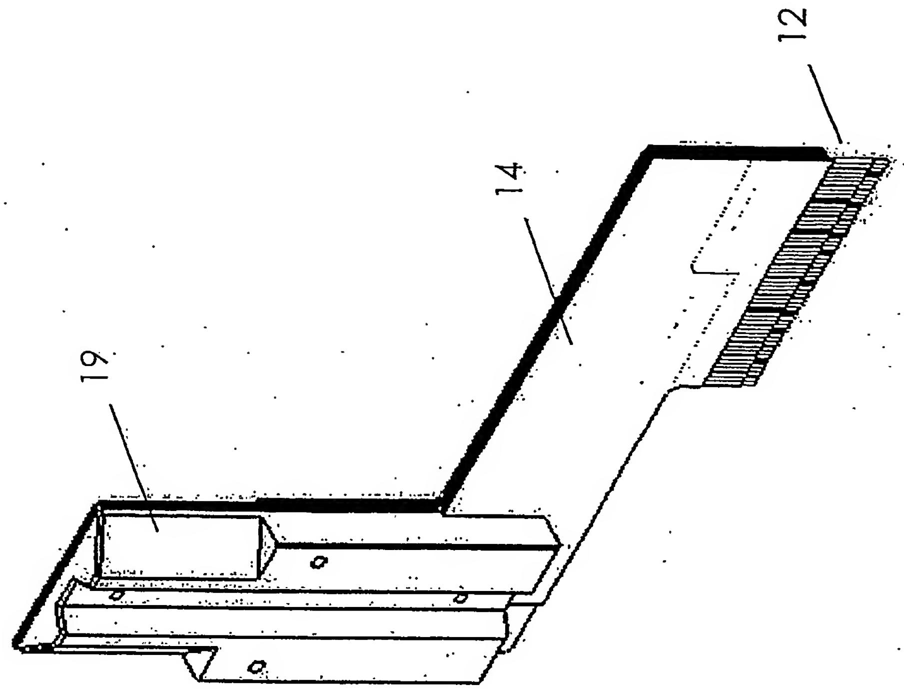


FIGURE 5C

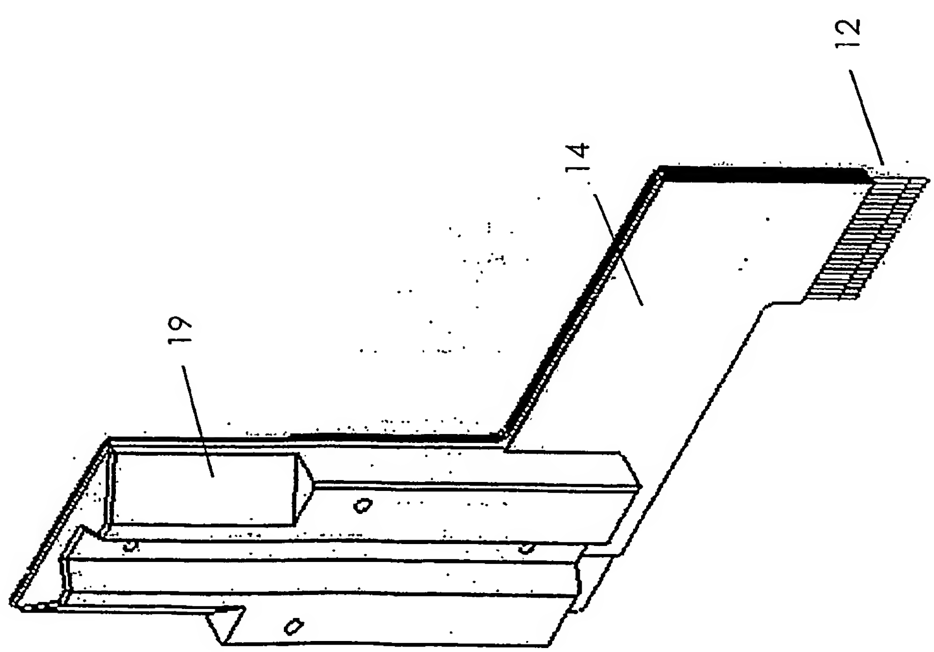


FIGURE 5E

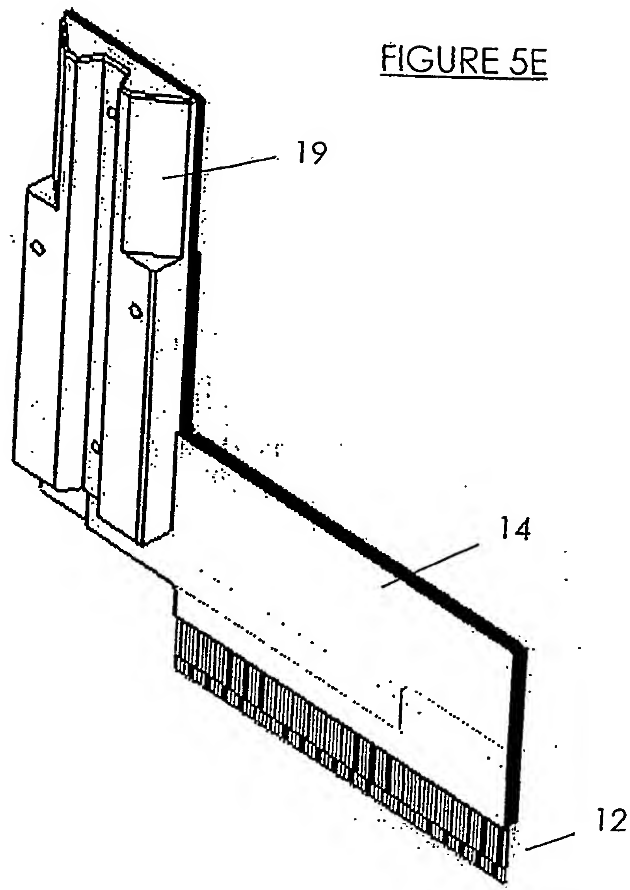
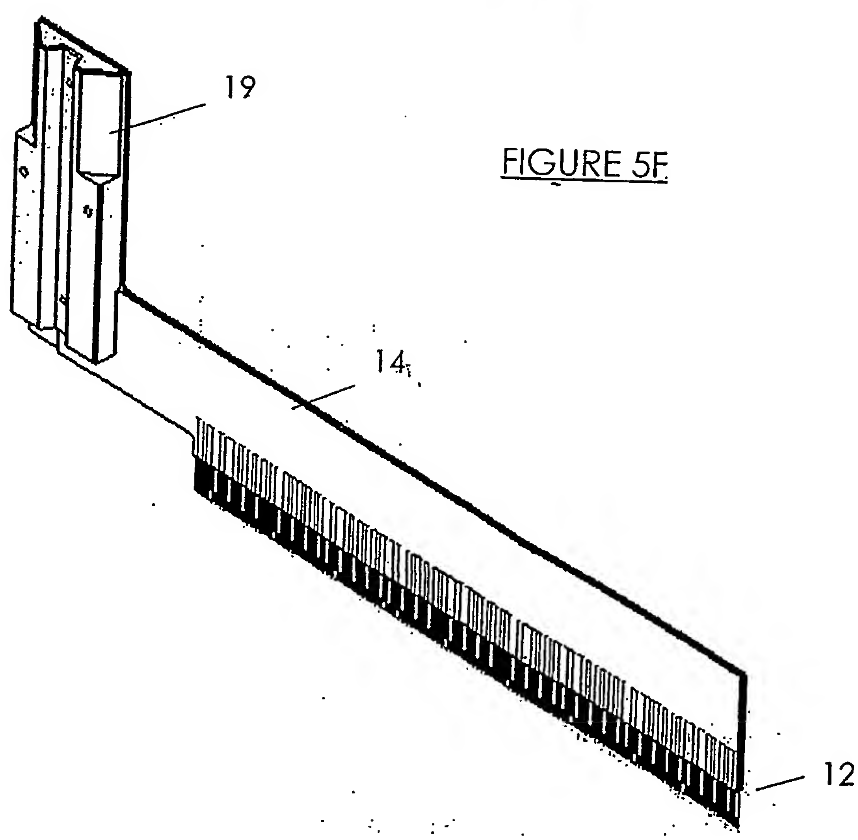


FIGURE 5F



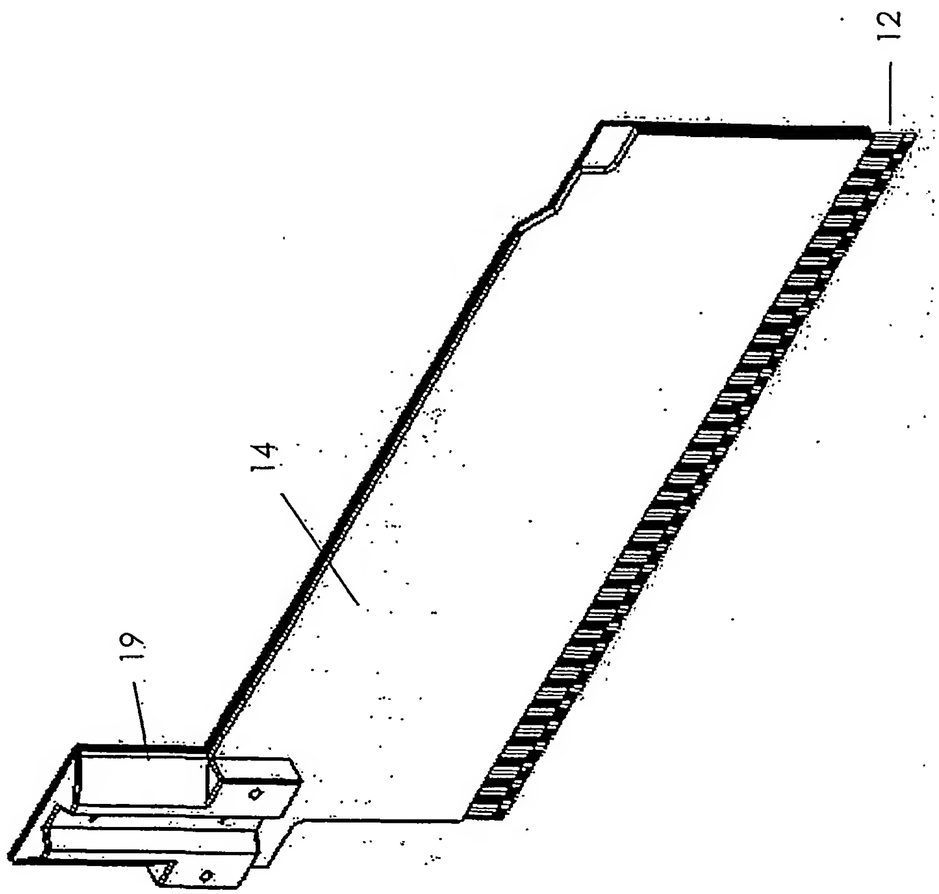


FIGURE 5G

FIGURE 5H

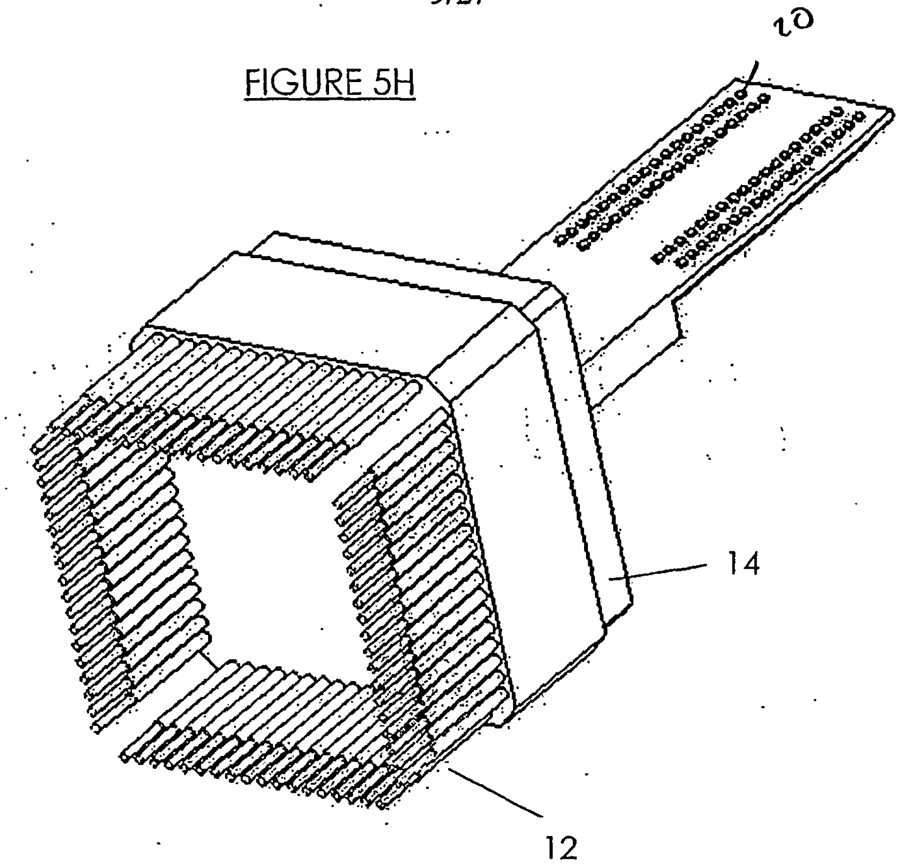


FIGURE 5I

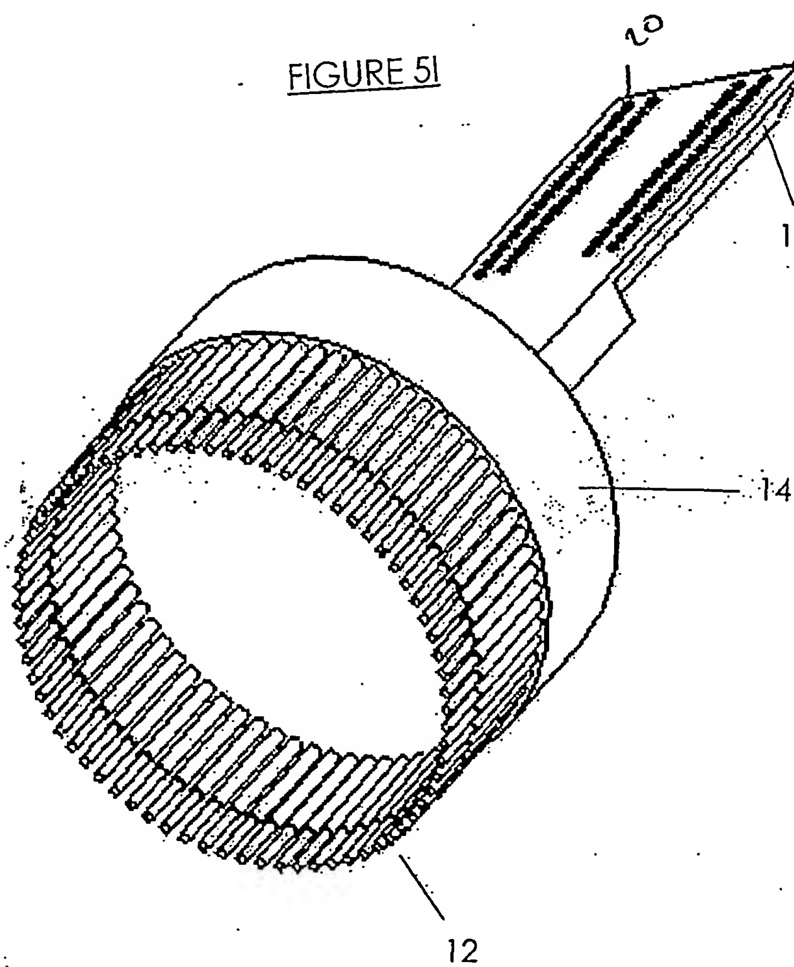


FIGURE 5J

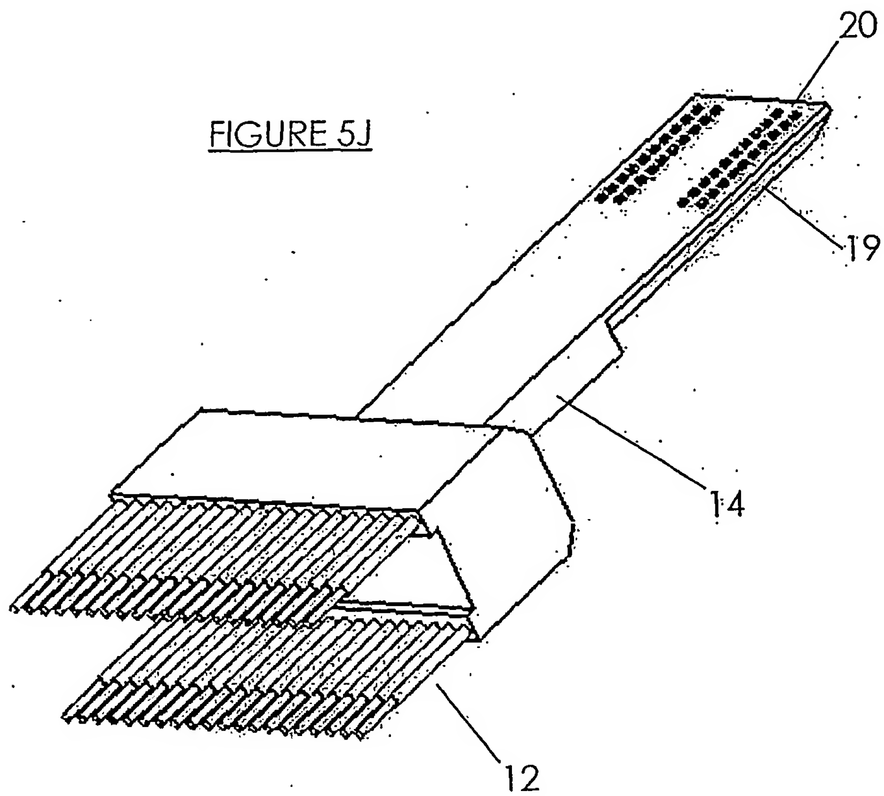


FIGURE 5K

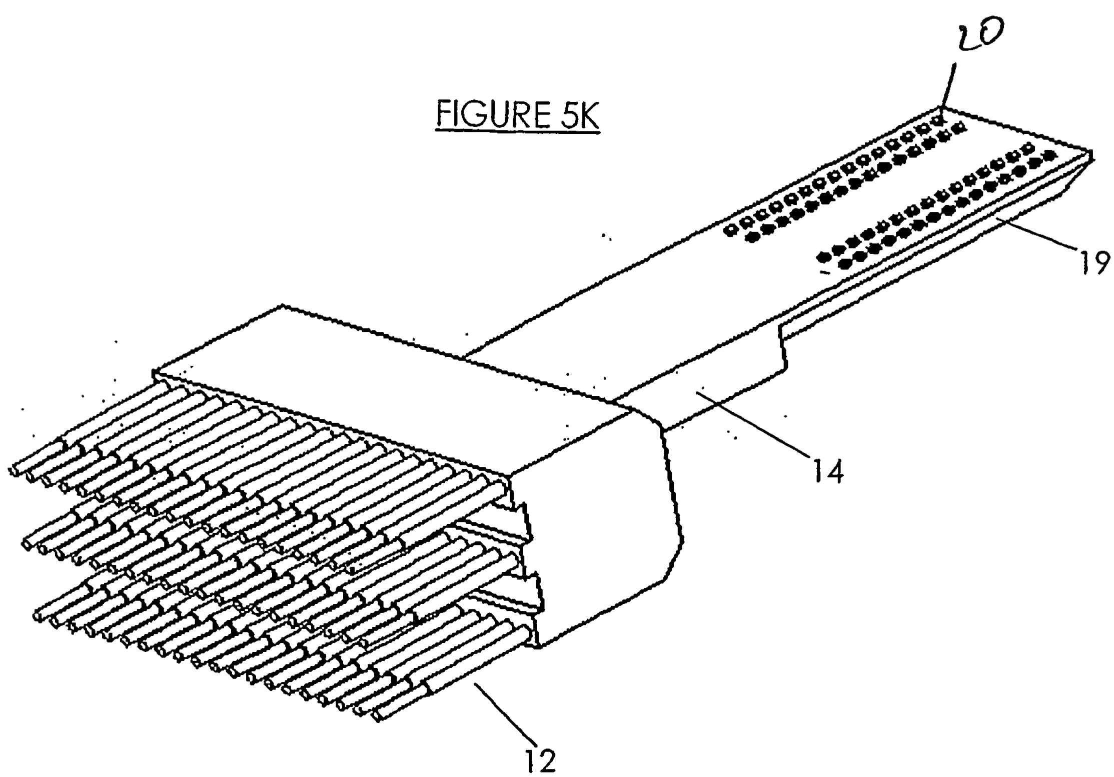


FIGURE 5L

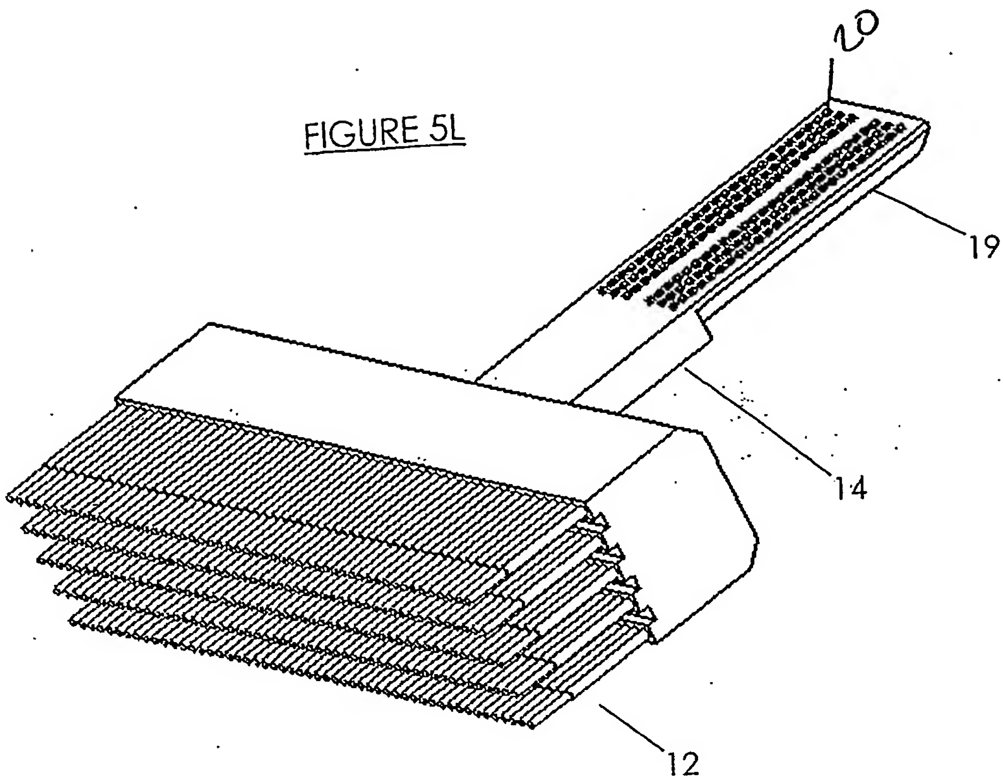
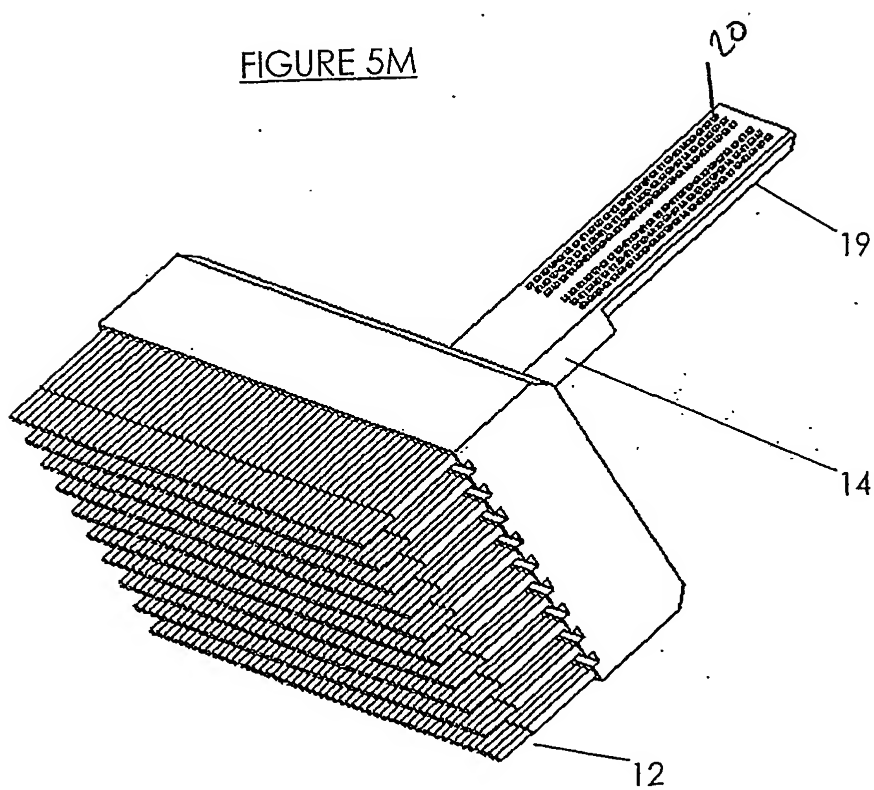


FIGURE 5M



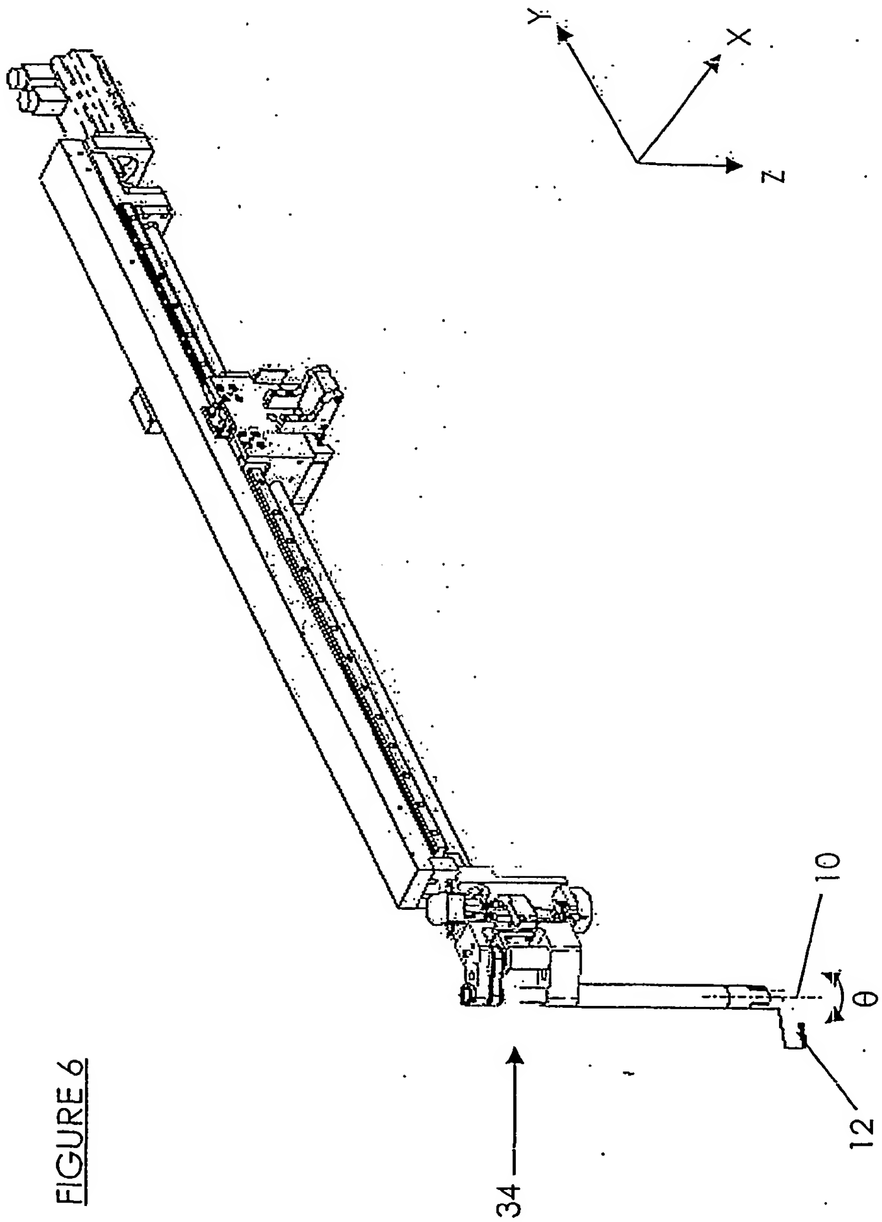


FIGURE 6

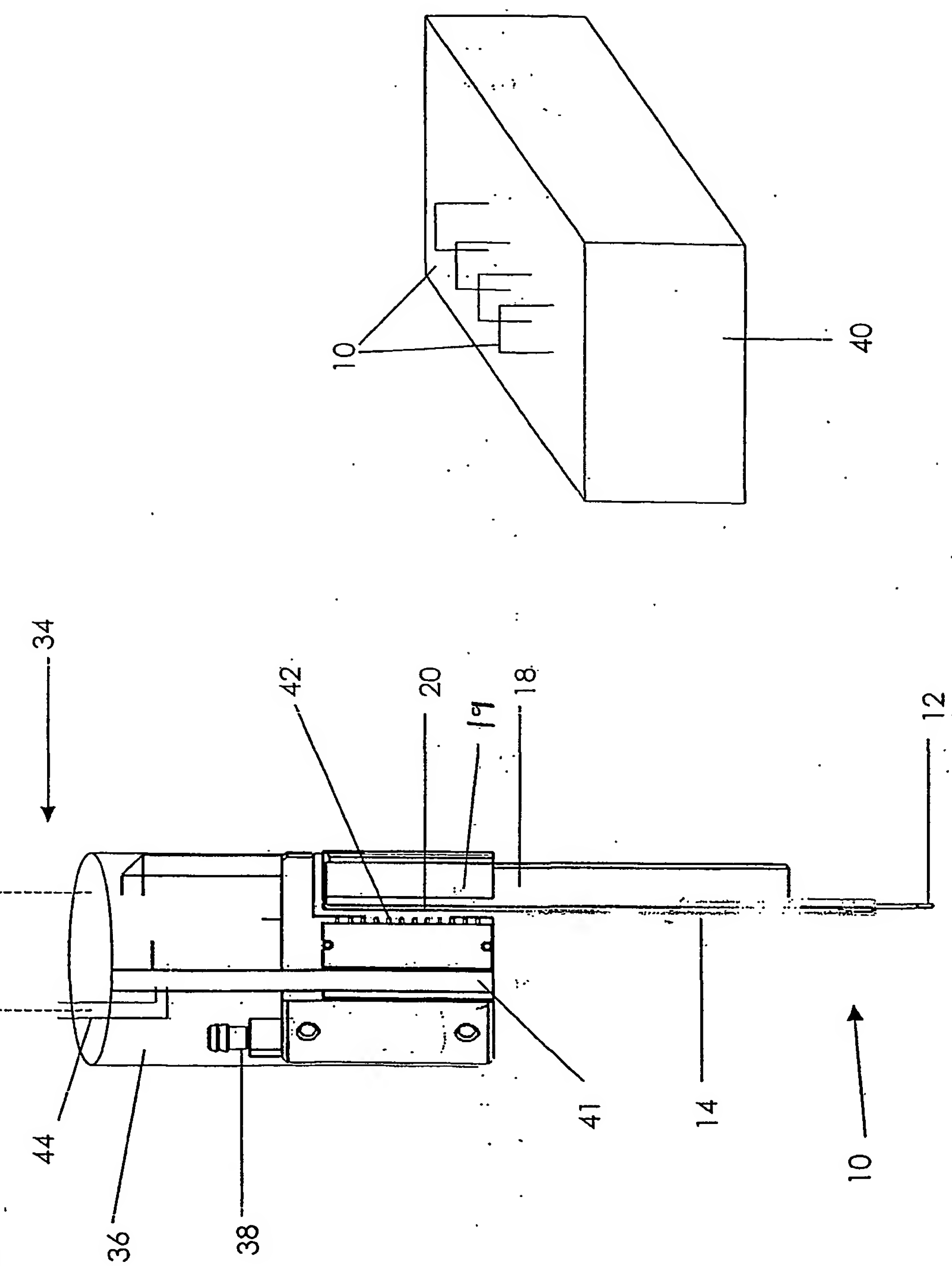


FIGURE 7

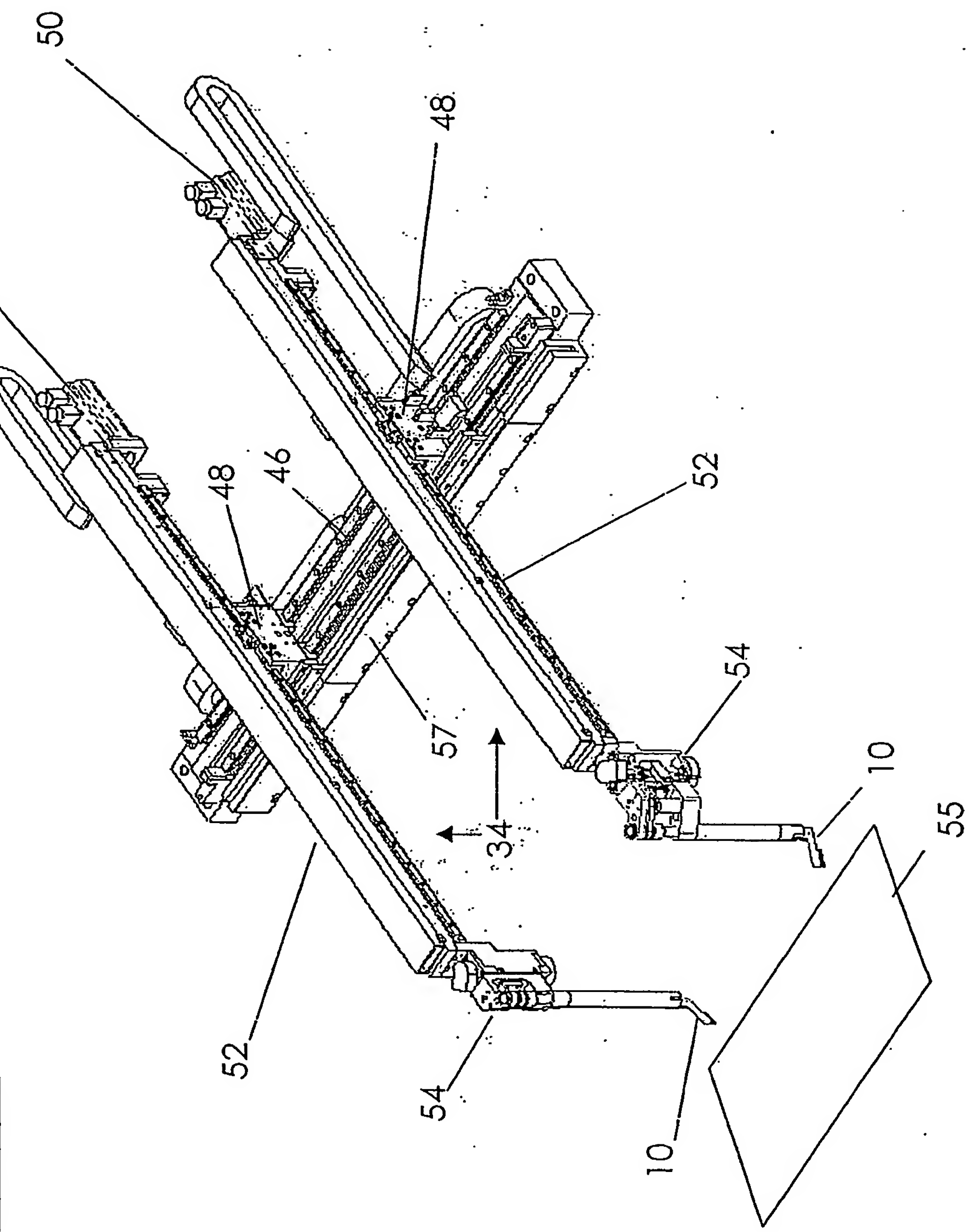


FIGURE 8A

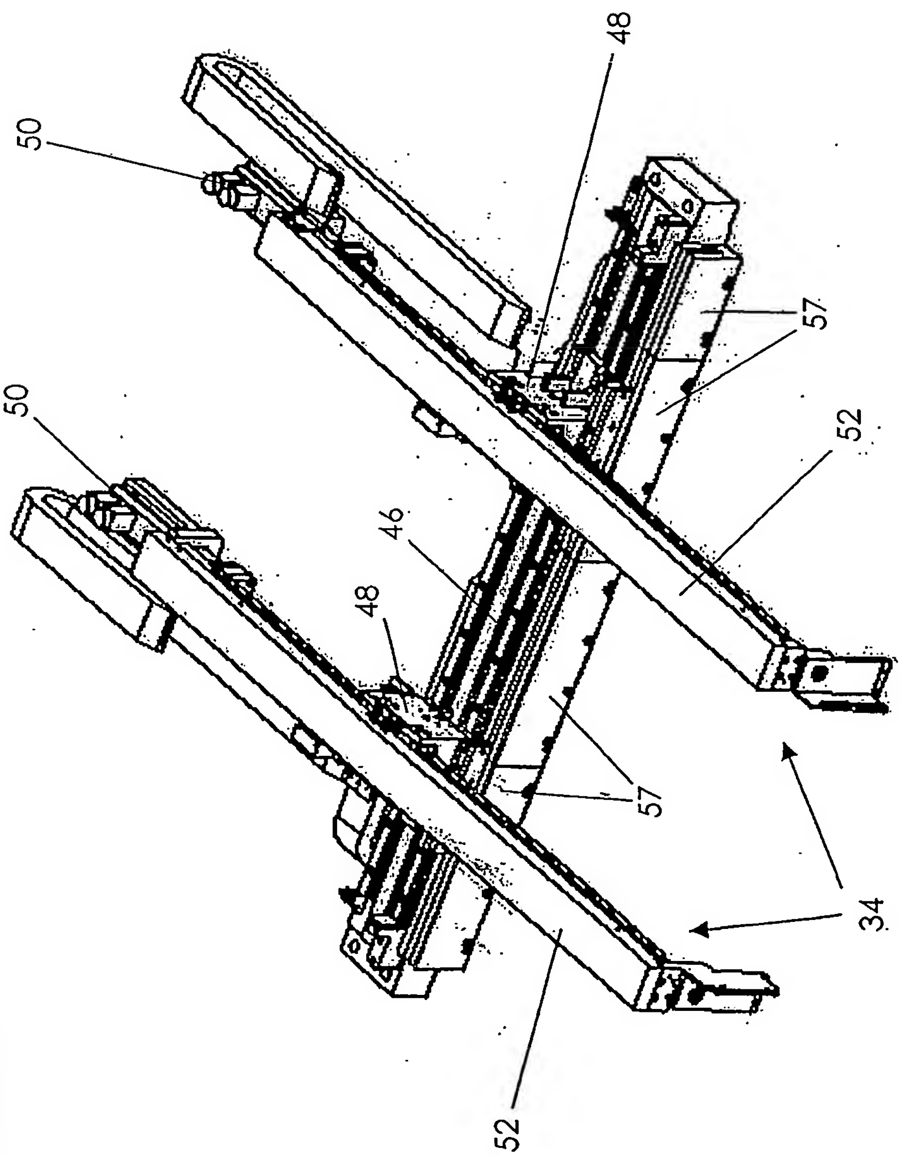


FIGURE 8B

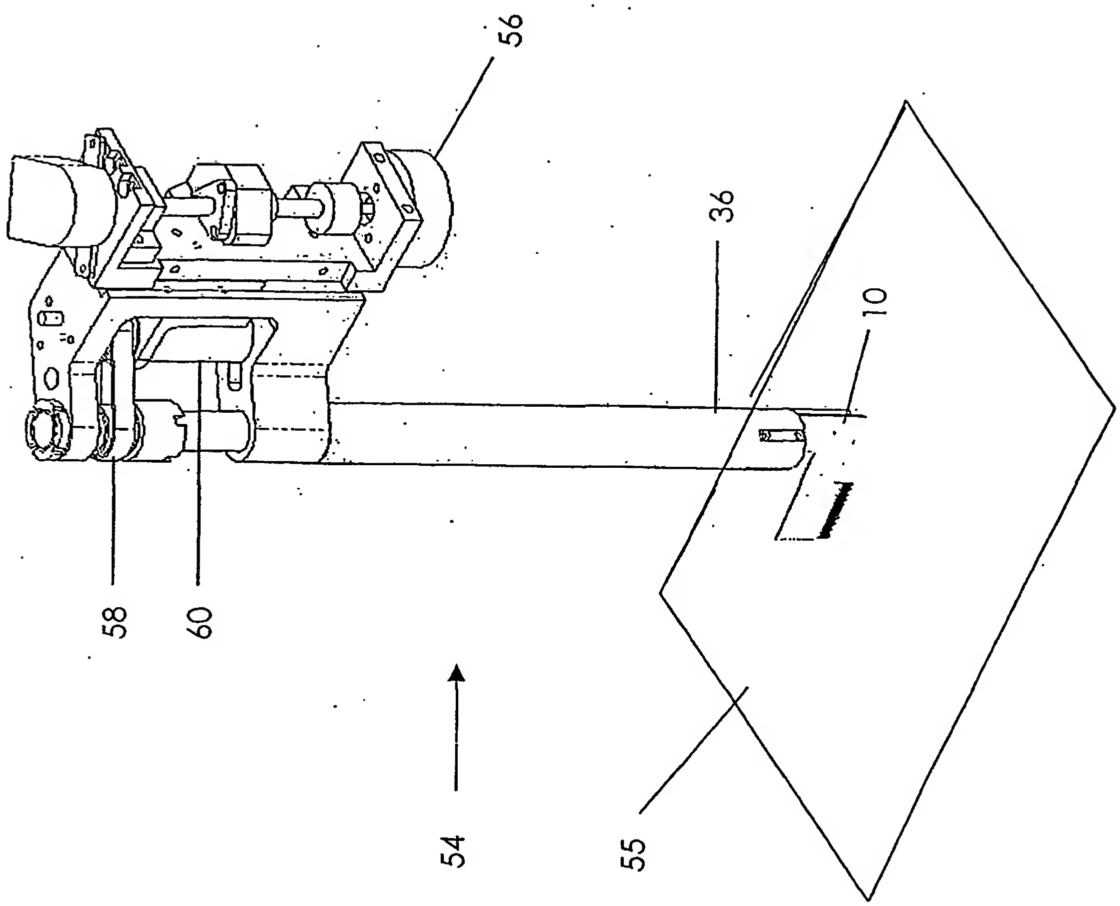


FIGURE 8C

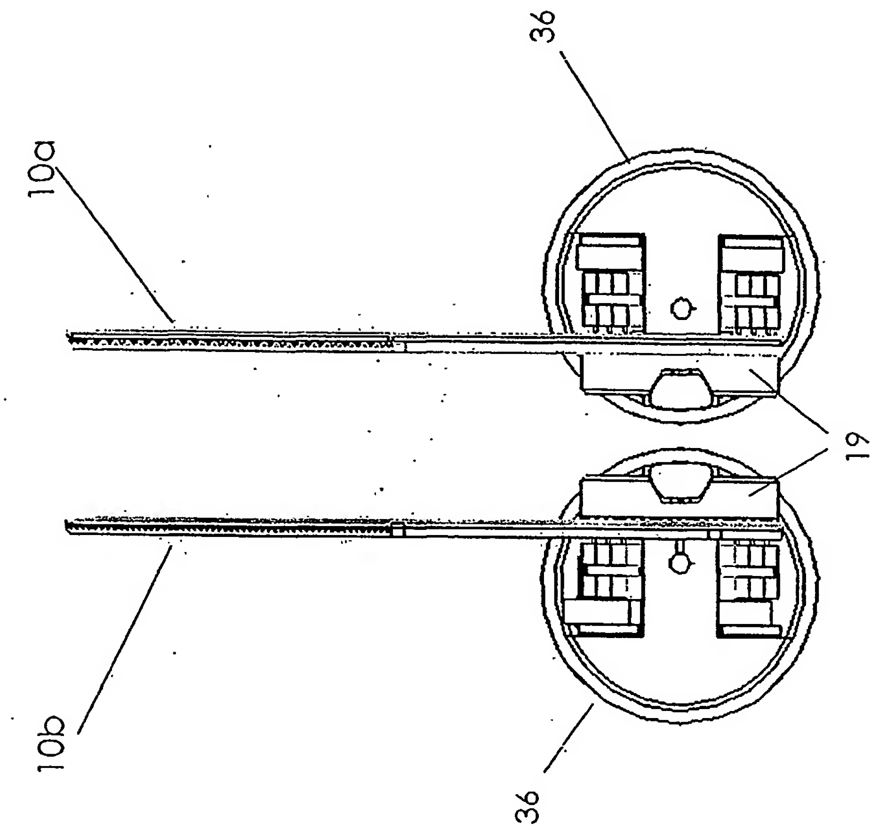
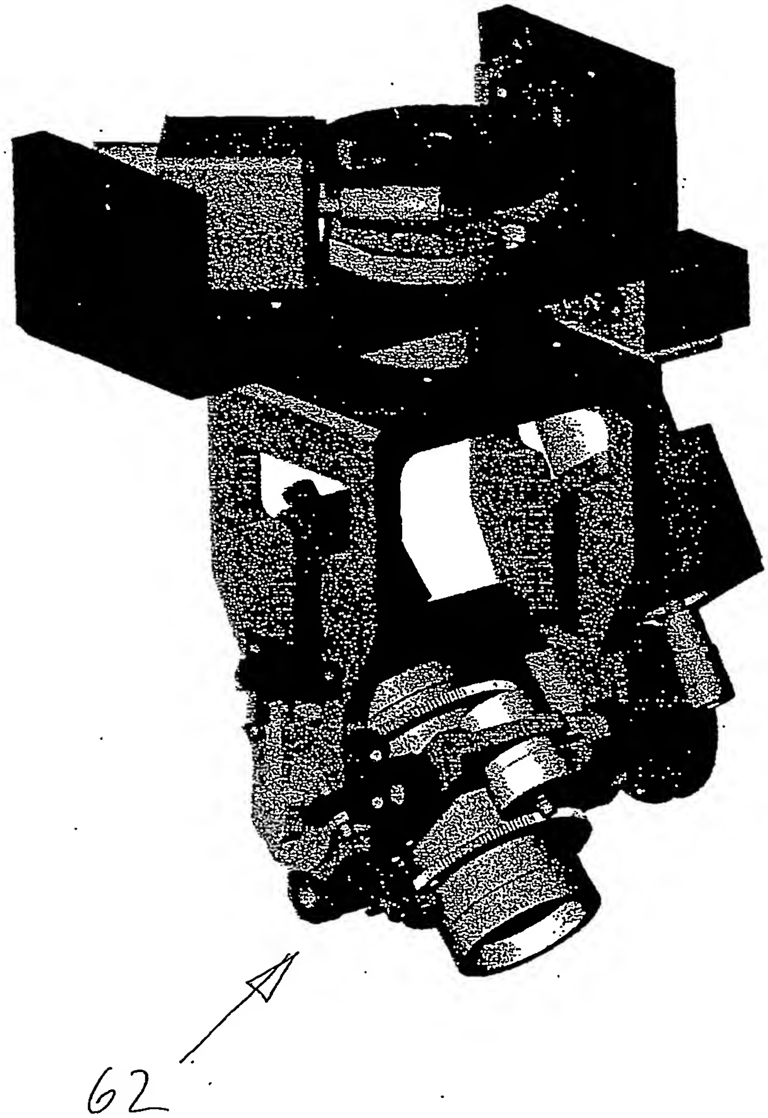


FIGURE 9

FIGURE 10



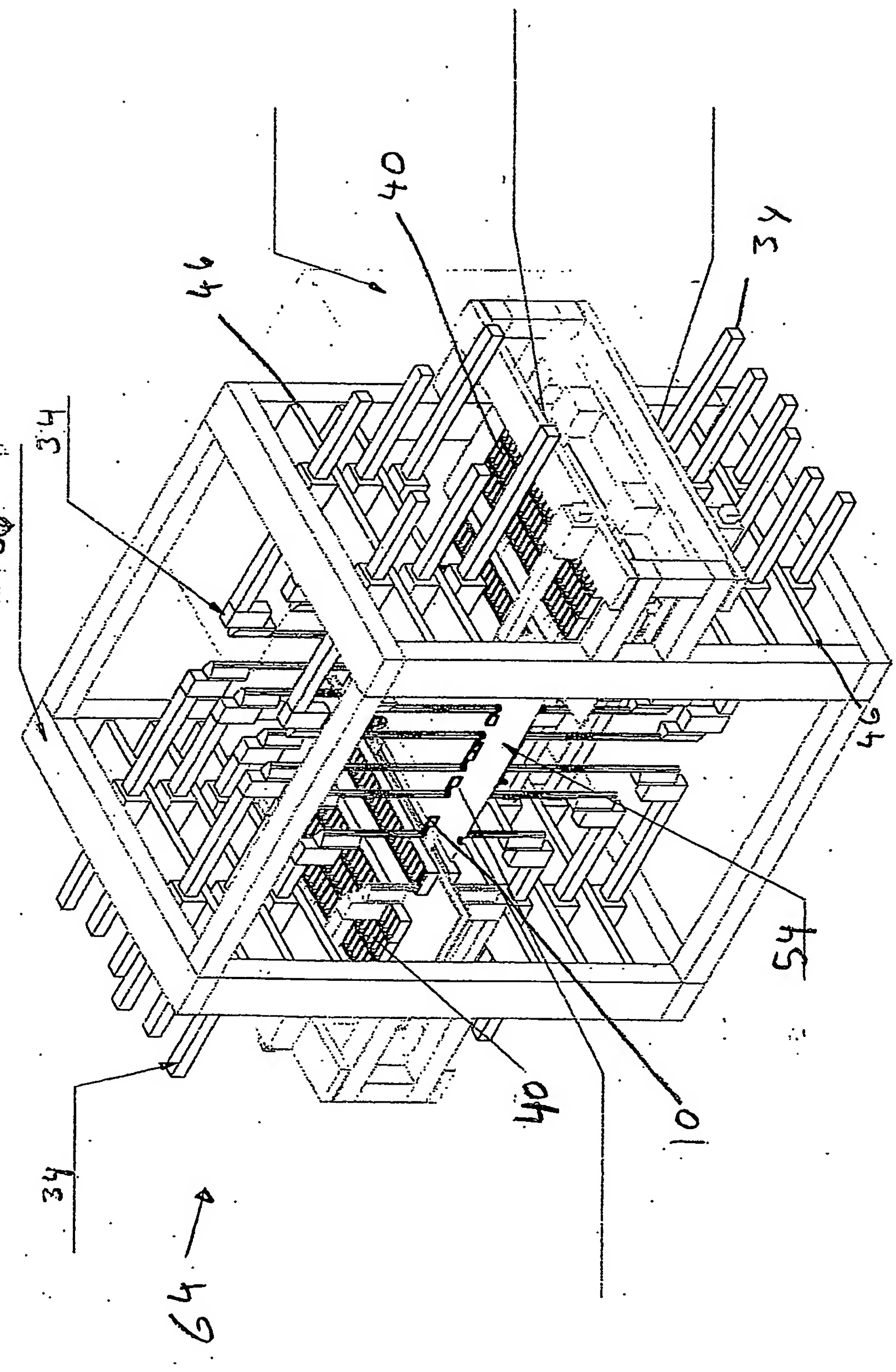


FIGURE 11

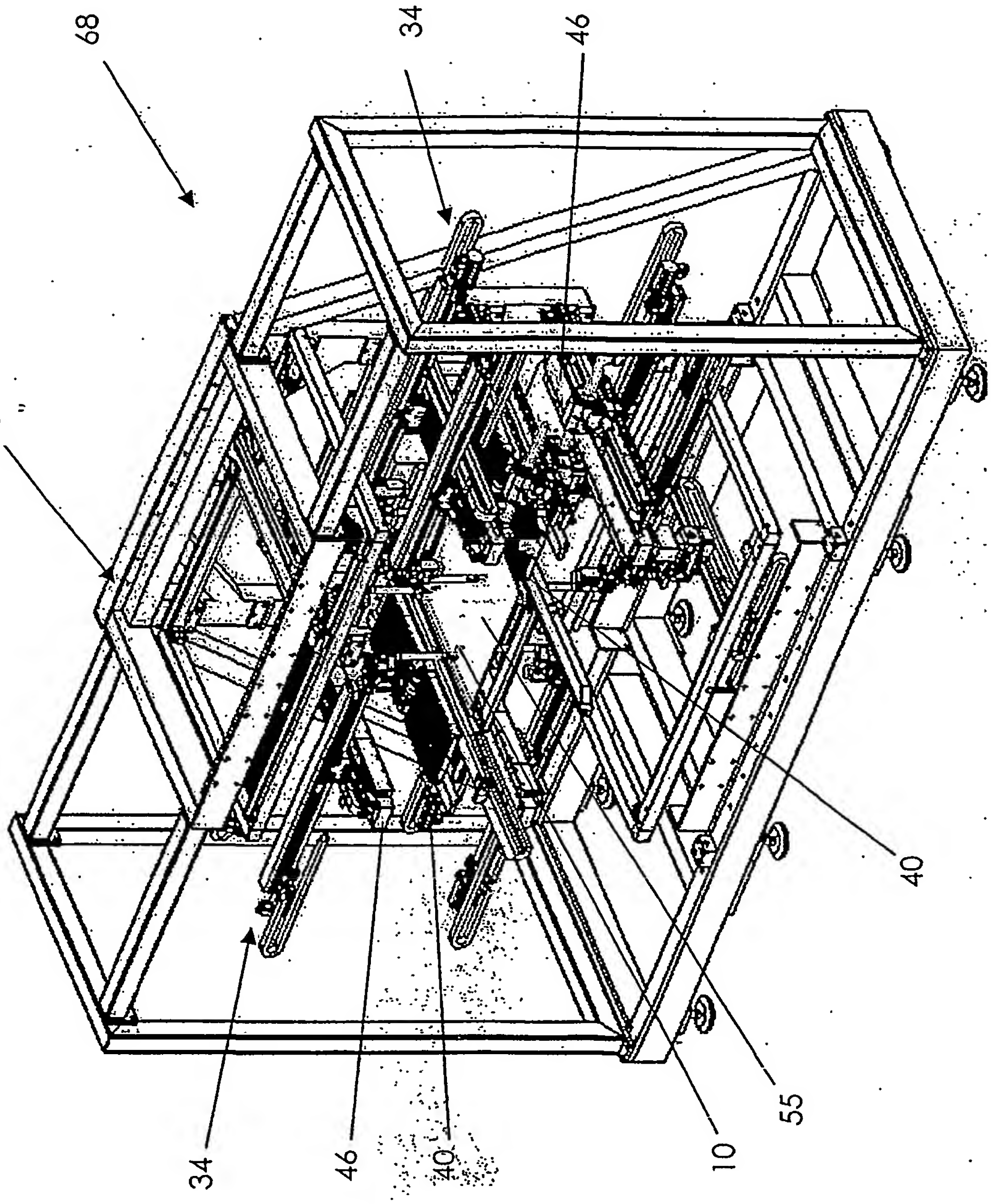


FIGURE 12

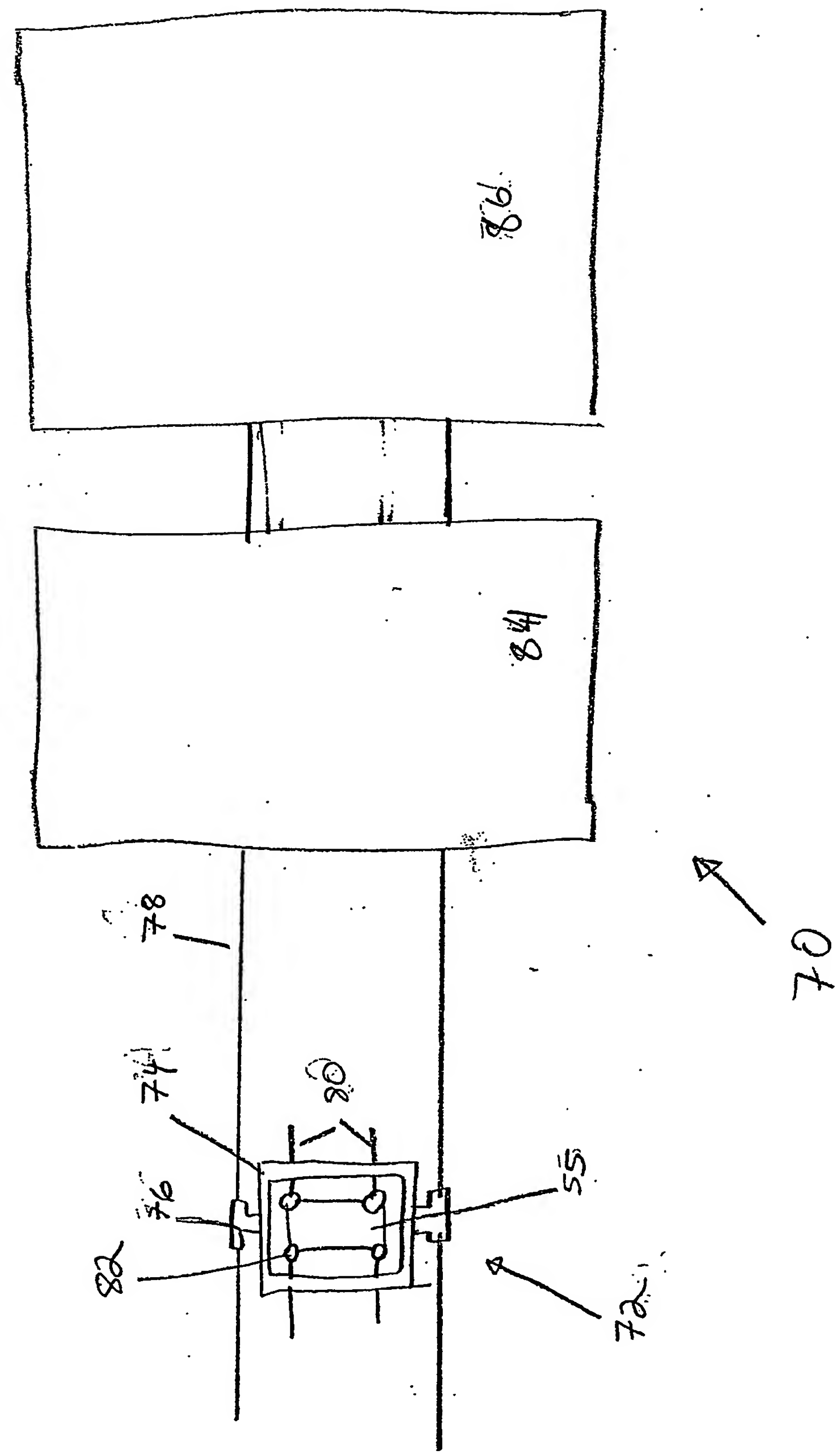


FIGURE 13

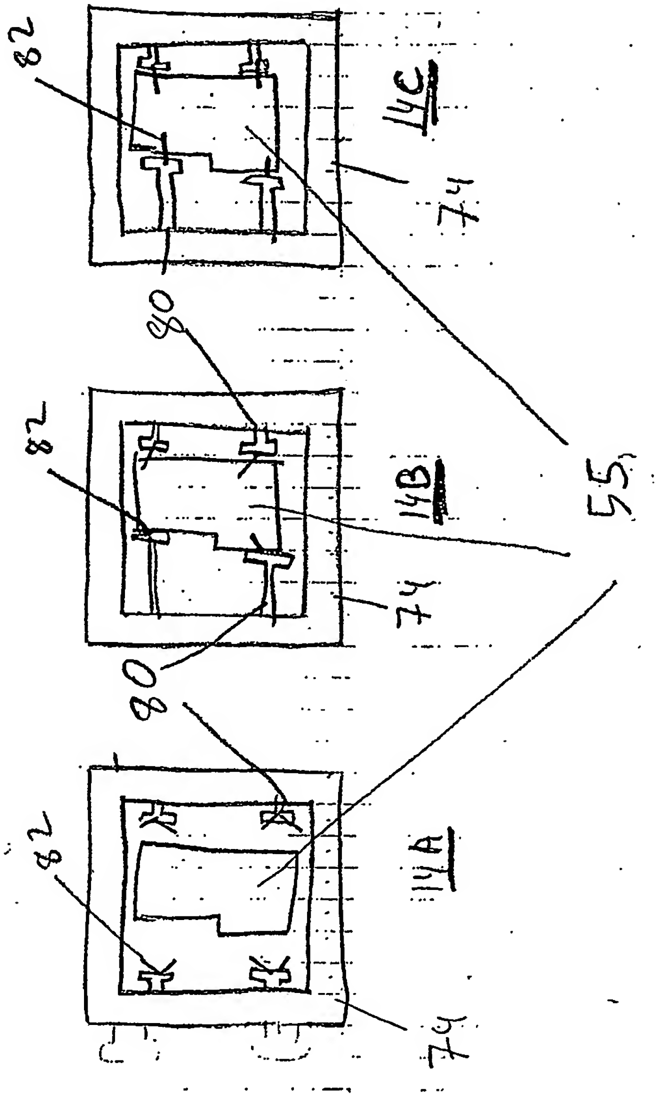


FIGURE 14

FIGURE 15A

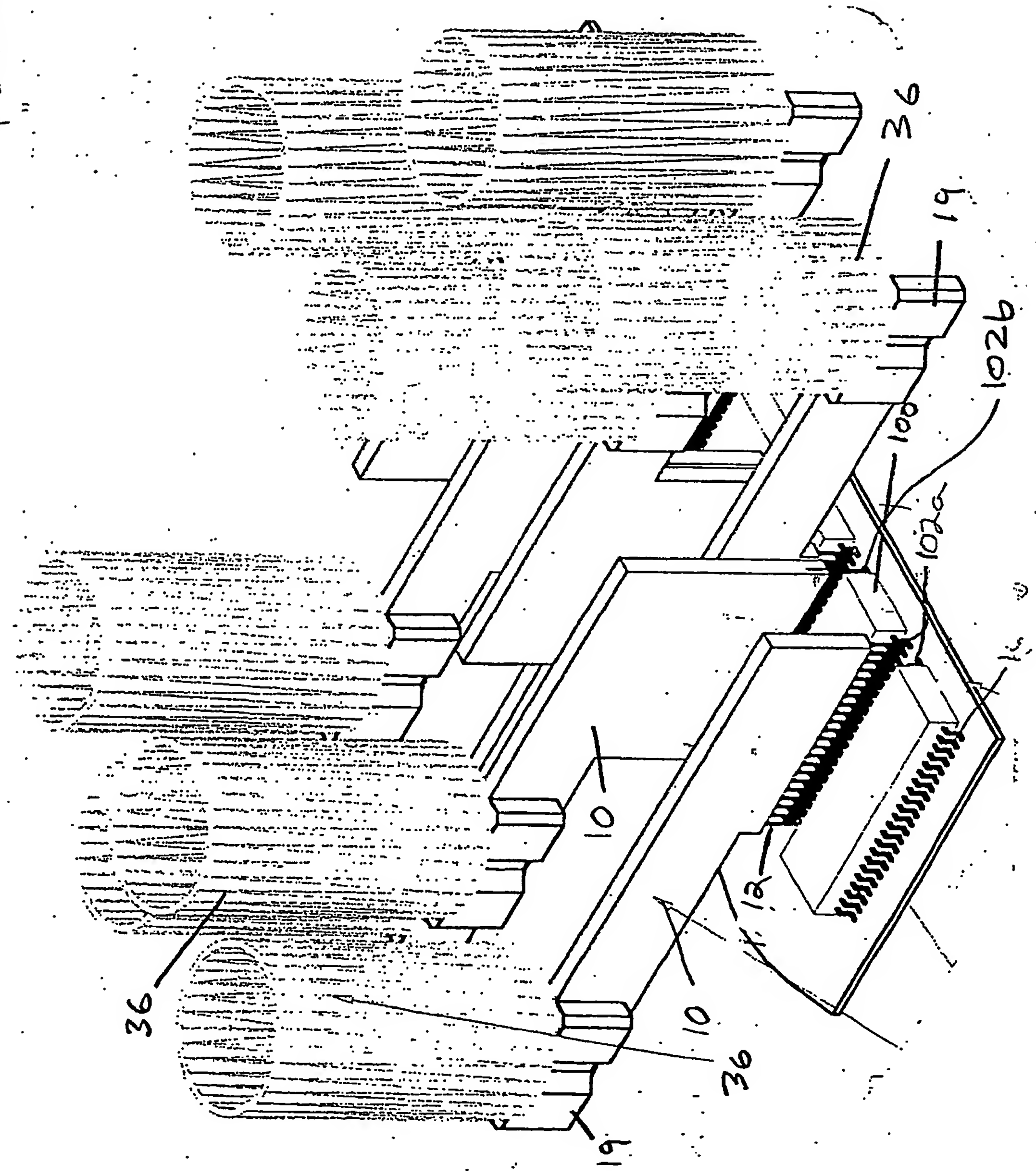


FIGURE 15B

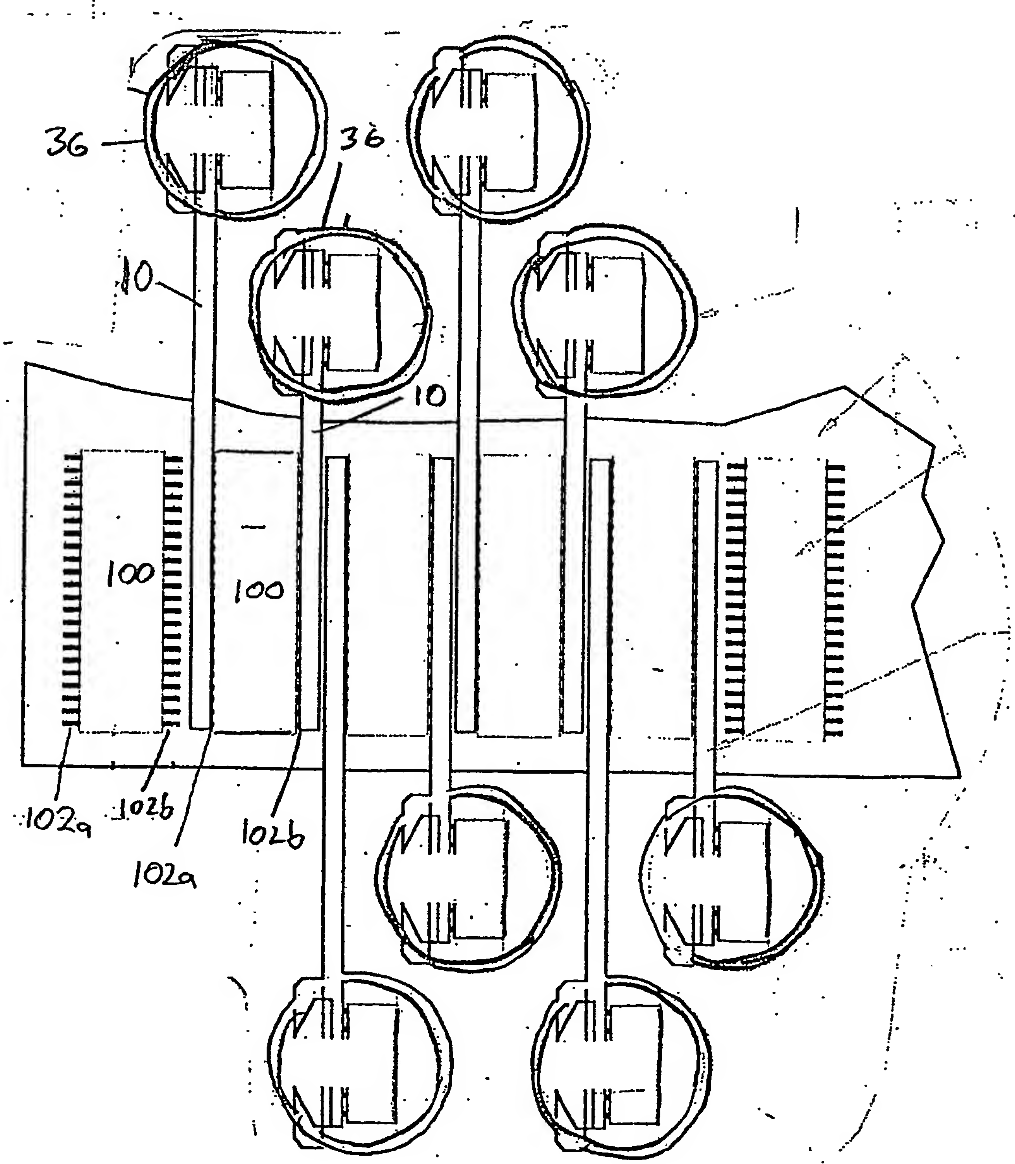


FIGURE 16A

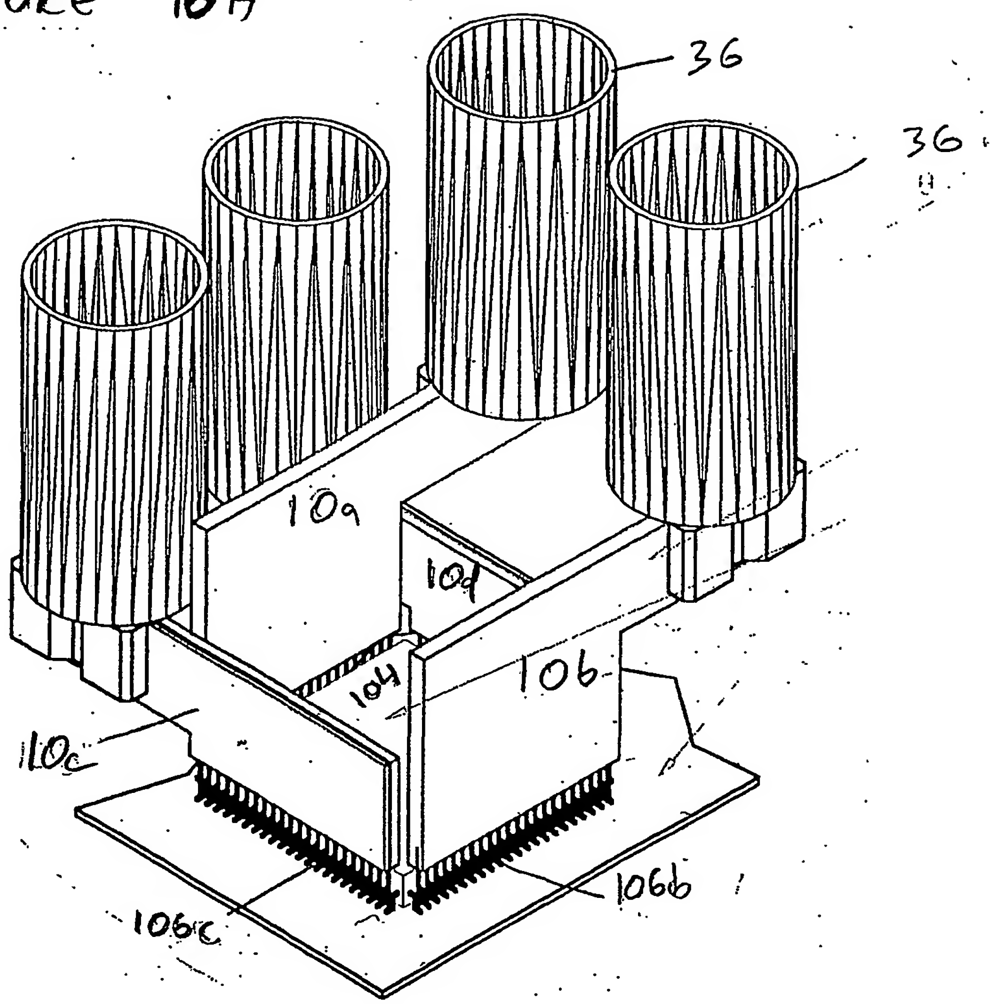
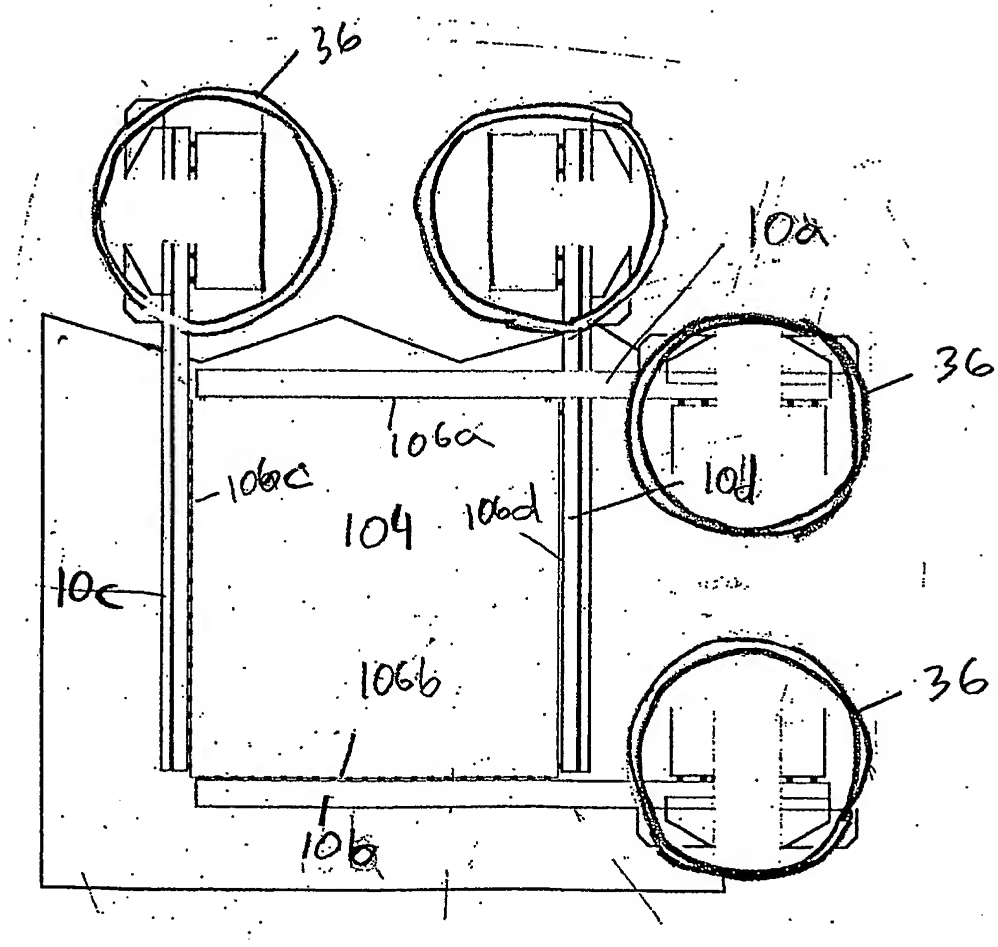


FIGURE 16B



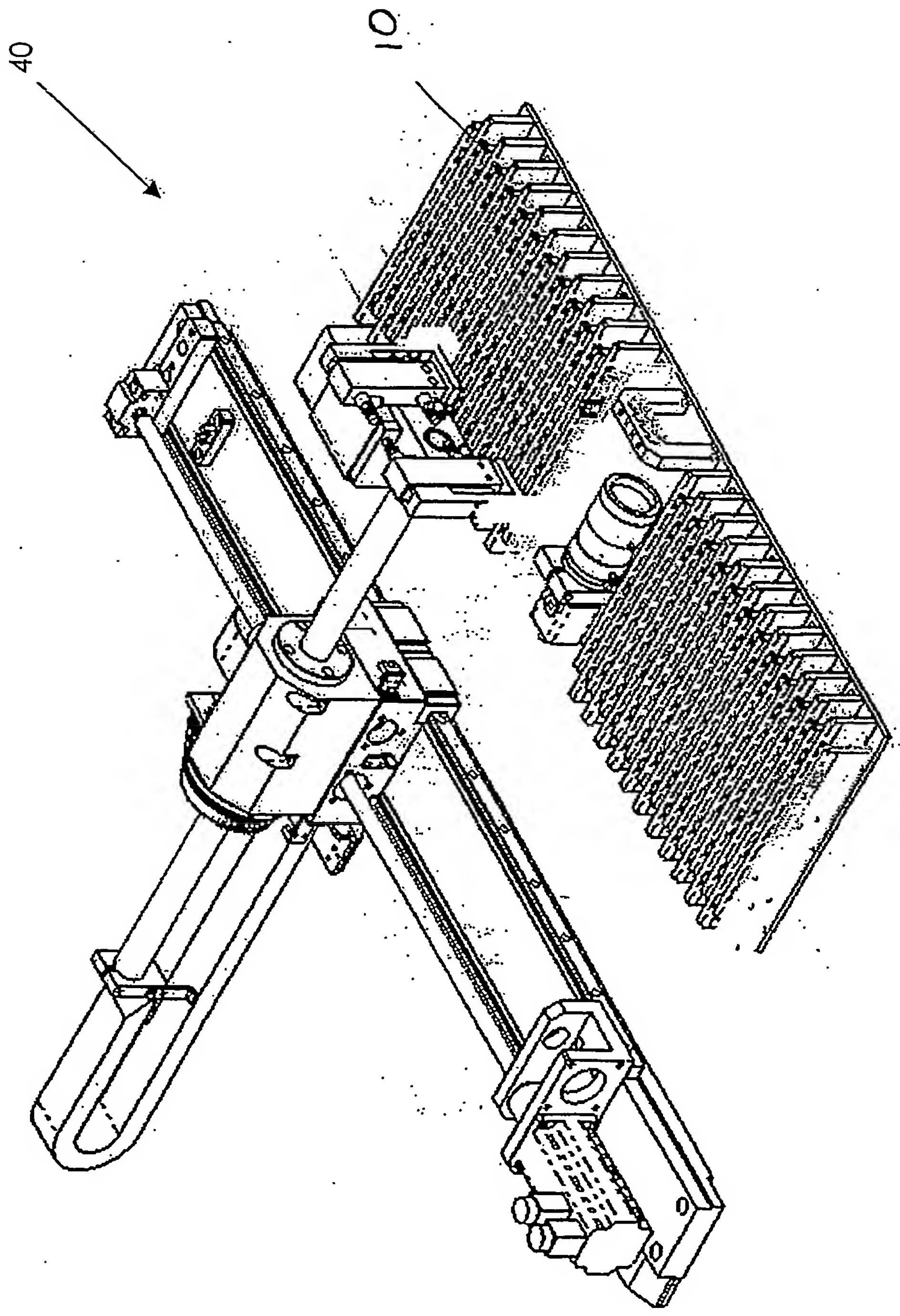


FIGURE 17